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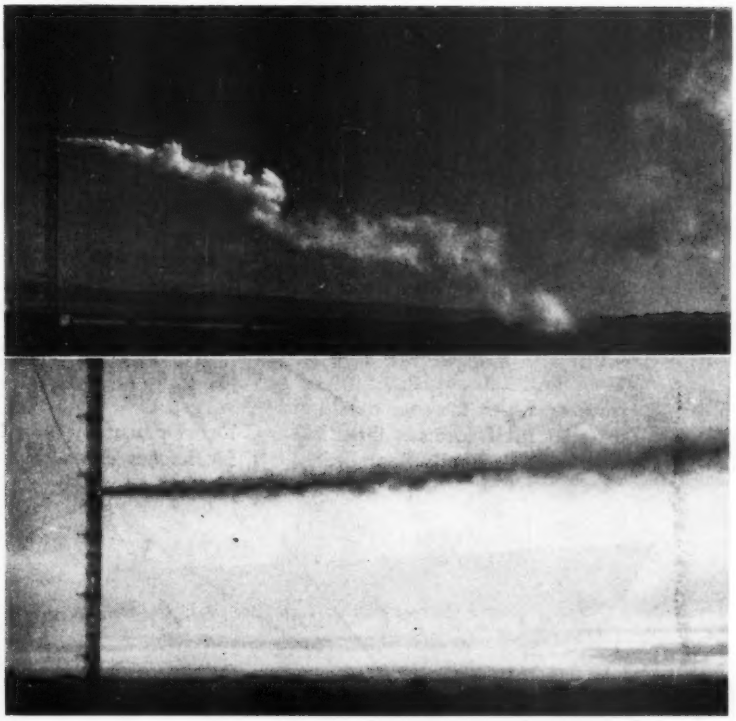

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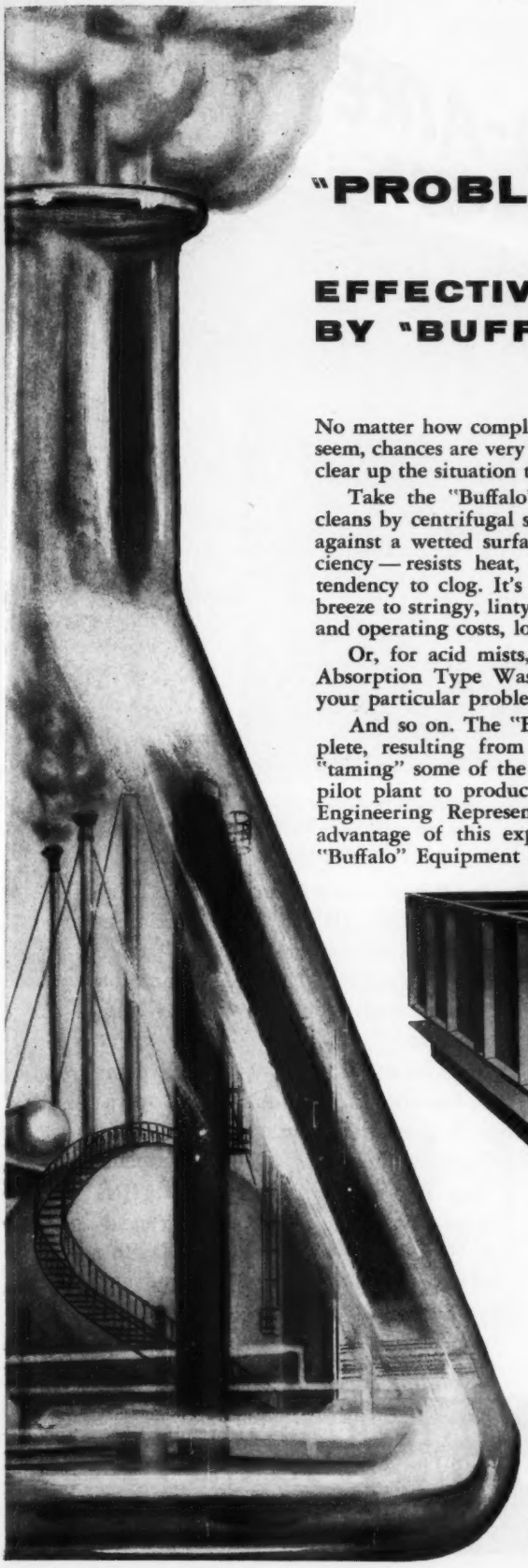

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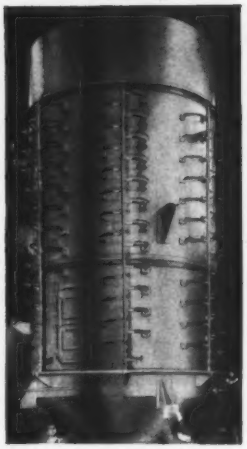

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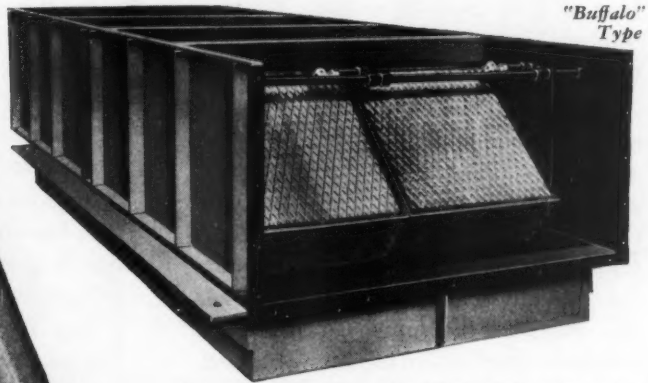

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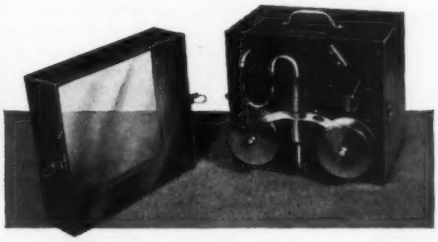

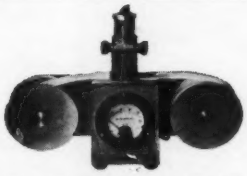

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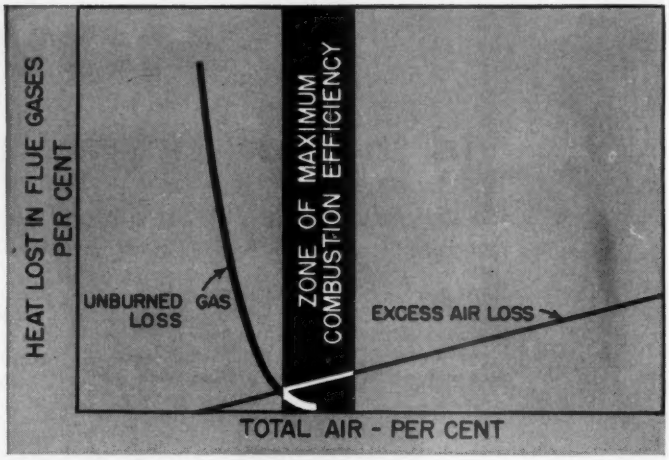
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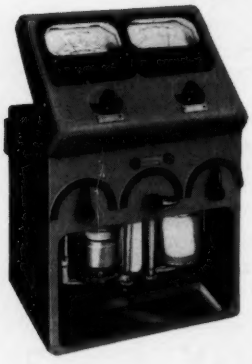

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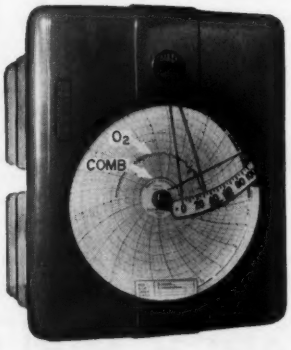

The Bailey Oxygen-Combustibles Analyzer-Recorder coordinates both records on one chart. These records enable the operator to keep fuel burning equipment performing continuously in the zone of maximum combustion efficiency. Excess air may be reduced to the point where combustibles begin to show.

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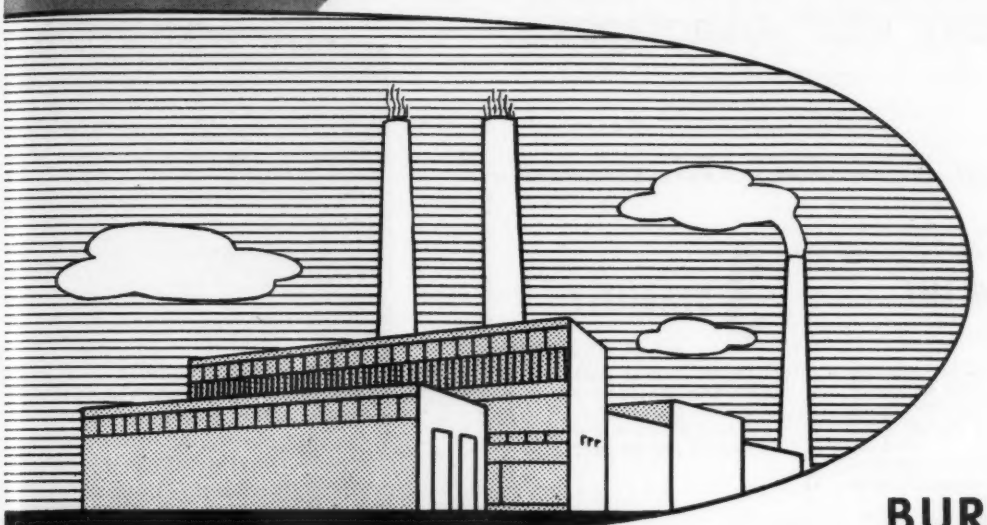
AIR POLLUTION... AND INCINERATION ENGINEERING



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d . . . Operating schedule?

e . . . Will surroundings dictate minimum height of stack?

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Formerly "Air Repair"

A QUARTERLY JOURNAL DEVOTED TO AIR PURIFICATION

Printed in the United States
Editor: H. C. BALLMAN
Editorial Asst.: JANE MILLER, T. GRAY
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AIR POLLUTION CONTROL ASSOCIATION
BOX 93
WILMERDING, PA.

Publications Committee 1956-57
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MAY 1957 — Vol. 7, No. 1

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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

THE JOURNAL OF THE AIR POLLUTION CONTROL ASSOCIATION is published quarterly by the Air Pollution Control Association, with editorial and executive offices at 609 Station Street, Wilmerding, Pa. Officially renamed Journal of the Air Pollution Control Association in May 1955. Name Air Repair eliminated November 1956.

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Automobile Exhaust and Smog Formation

W. L. FAITH
Air Pollution Foundation
Los Angeles, Calif.

JOHN T. GOODWIN, JR., F. V. MORRISS, and CALVIN BOLZE
Midwest Research Institute
Kansas City, Mo.

There is general agreement that the undesirable manifestations of Los Angeles smog result from a photochemical reaction between hydrocarbons (more accurately, *organics*) and nitrogen oxides present in very small quantities in the atmosphere.[3,4,5] The chief uncontrolled source of these compounds is automobile exhaust.[1,2] To determine how much the various constituents of auto exhaust must be reduced to eliminate undesirable smog manifestations, a research project was initiated at Midwest Research Institute, Kansas City, Missouri.

Two large (2200 ft.^{3} each) glasshouses (Fig. 1) were built, in which auto exhaust and other pollutants could be subjected to the action of sunlight. Pollutants added to the chambers in measured amounts were nitric oxide (NO), nitrogen dioxide (NO_2), 3-methylpentane, hexene-1, and exhaust from a 1952 automobile, idling at 500 rpm. The chambers were fitted with equipment suitable to measure continuously the oxidant level of the atmosphere in the greenhouse, as well as nitric oxide and nitrogen dioxide. Oxidant, by rubber cracking, was also measured by 2 ozonometers. Eye irritation was evaluated by a panel of 20 students, who entered the chambers at various predetermined intervals after the pollutants were admitted. Measurements of temperature, relative humidity, and light intensity were also made continuously. Total hydrocarbons, sulfur dioxide, carbon monoxide, and aldehydes were measured at regular intervals during each experiment, which usually ran for 90 minutes.

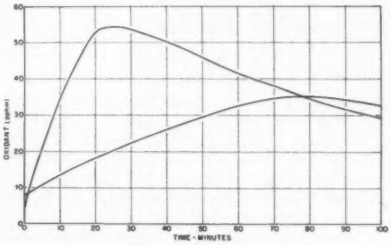

Fig. 2. Typical oxidant curves.

A series of 64 experiments was designed[6] in which nitric oxide, nitrogen dioxide, and hydrocarbons were each studied at 4 concentrations. Four combinations of auto exhaust and added hydrocarbon were also studied.

Qualitative Results

The most marked observation that resulted from this series of experiments was the rapidity with which the odor of raw exhaust changed to a typical smog odor under the influence of sunlight. Another was the range of the eye-irritation response reported by the panel members. This was similar to the response in Los Angeles, where some people never experience eye irritation and others are quite susceptible.

In all cases, oxidant formation began almost immediately upon charging the chamber, but the rate of rise varied considerably from one experiment to another. (Control experiments performed at night showed no oxidant formation.) Typical oxidant curves are shown in Fig. 2. In one case the rise is rapid; in the other, much slower. Further, in all runs, the NO measurement decreased throughout the run, and the NO_2 value first increased and then decreased (Fig. 3). Generally, as long as NO was present, oxidant concentration remained low; after NO had been converted to NO_2, the oxidant concentration increased more rapidly. All of these effects are noticeable in the Los Angeles atmosphere. It is obvious, therefore, that air containing hydrocarbons from auto exhaust and oxides of nitrogen in the concentration range studied can

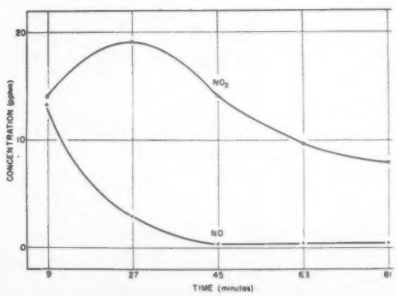

Fig. 3. Typical NO-NO_2 curve.

Fig. 1. Smog chambers.

[1] W. L. Faith. The Atmospheric Hydrocarbon Problem in Los Angeles County, Air Pollution Foundation, Los Angeles. (Published in part under the title What Causes Smog? in *Refining Engr.*, Oct. 1956.)

[2] W. L. Faith. Methods and Devices for Controlling the Hydrocarbon Content of Automobile Exhaust Gases, *SAE Special Publication No.* 139 (1955).

[3] A. J. Haagen-Smit. Chemistry and Physiology of Los Angeles Smog, *Ind. Eng. Chem.* 44, 1342-6 (1952).

[4] P. A. Leighton and W. A. Perkins. Solar Radiation, Absorption Rates, and Photochemical Primary Processes in Urban Air, Rept. No. 14, Air Pollution Foundation, Los Angeles (March 1956).

[5] Stanford Research Institute. The Smog Problem in Los Angeles County. Western Oil and Gas Association, Los Angeles (1954).

[6] Statistically, the experimental design was a quarter replicate of a $4^3 \times 2^2$ factorial. Runs were randomized as to north and south chambers and morning and afternoon runs, as well as to pollutant concentrations.

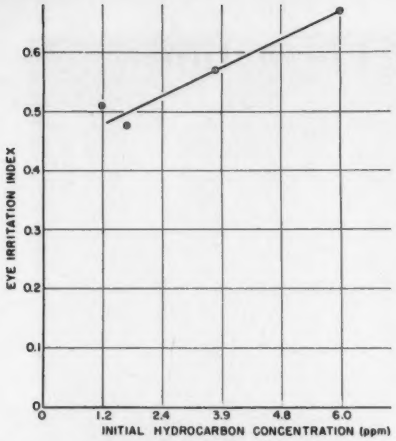

Fig. 4. Effect of hydrocarbon concentration on eye irritation index.

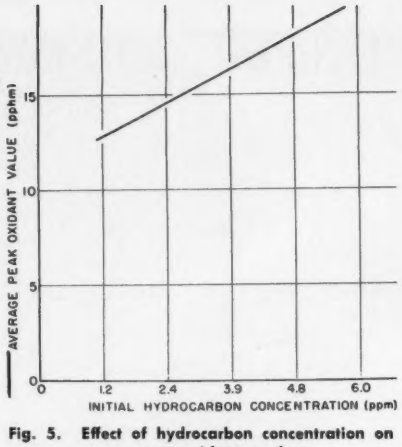

Fig. 5. Effect of hydrocarbon concentration on average oxidant peak.

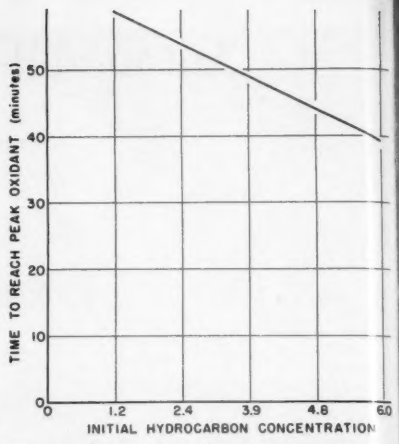

Fig. 6. Effect of hydrocarbon concentration (ppm.) on time to reach peak oxidant.

produce at least 2 of the smog effects (high oxidant formation and eye irritation) noticed in Los Angeles.

Statistical Conclusions

The data were examined for statistically sound conclusions. The more important ones are given in the following discussion.[7] Only those correlations with a degree of confidence of 0.95-or-better are mentioned.

The major effects found are listed under pertinent headings.

Effect of Hydrocarbon Level[8]

1. The severity of eye irritation increased as the amount of hydrocarbon charged to the chamber was increased. This is represented graphically in Fig. 4.

2. The peak oxidant value (KI recorder) increased as the level of the hydrocarbon charged was increased (Fig. 5).

3. The rate of oxidant formation increased as the level of hydrocarbon charged was increased. In other words, the time required to reach the oxidant peak decreased as the hydrocarbon level was increased (Fig. 6).

Effect of Hydrocarbon Type

1. The most noticeable effect of hydrocarbon type was that of 3-methylpentane on the rate of formation of oxidant. In all cases where 3-methylpentane was substituted for part of the exhaust hydrocarbon, the time required to reach a peak oxidant value was increased. This is shown dramatically in Fig. 7 and 8. The substitution of hexene-1 for part of the idling exhaust showed a similar, but less striking, reduction in peak oxidant value.

2. The rate of oxidant formation increased as the percentage of exhaust hydrocarbons in the total hydrocarbon charge was increased (Fig. 9). In reviewing the various experiments it was plain that as exhaust hydrocarbon percentage increased, oxidant formation was more rapid, the oxidant peaked earlier, and then was decreasing through the major portion of the experiment.

These variations in rate of formation of oxidant point out very clearly that

[7] The complete data and all correlations (significant or not) will be published as a special report by the Air Pollution Foundation.

[8] The four levels of hydrocarbon charged to the chamber were 1.2, 2.1, 3.5, and 6.0 ppm. However, one should not extrapolate these values to the values actually found by analysis of the Los Angeles atmosphere. When the air in the glass chambers was analyzed for hydrocarbon content (by freezeout-infrared technique) the values found varied from 25 to 100% of the input, depending on the level of nitrogen oxides charged. This finding casts considerable doubt on the method currently used in determining atmospheric hydrocarbons. Probably the values used in the experiments herein reported are similar to those actually existing in the atmosphere.

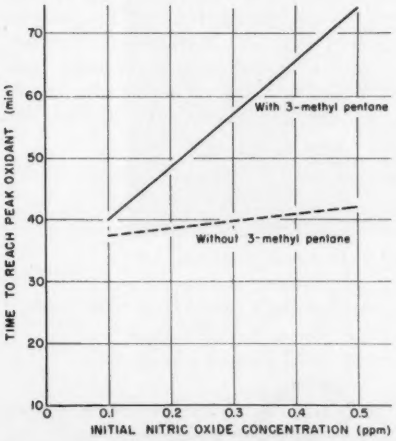

Fig. 7. Effect of NO concentrations on time to reach peak oxidant.

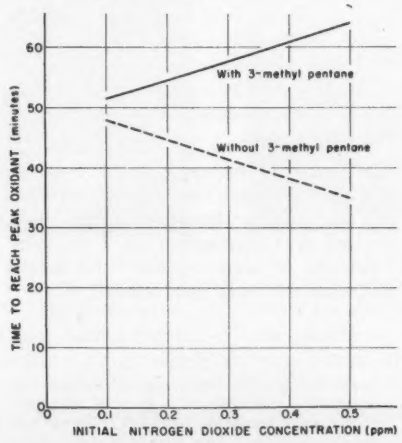

Fig. 8. Effect of NO_2 concentration on time to reach peak oxidant.

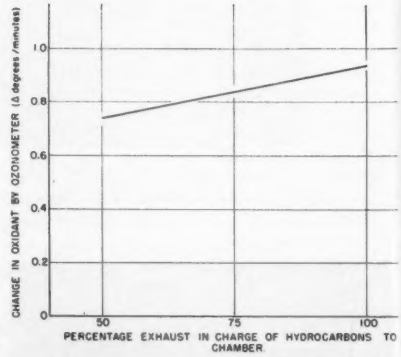

Fig. 9. Effect of percentage exhaust in hydrocarbon charge on oxidant formation.

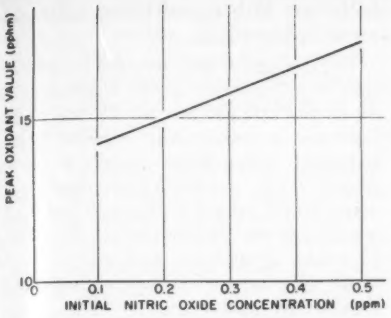

Fig. 10. Effect of initial NO level on peak oxidant value.

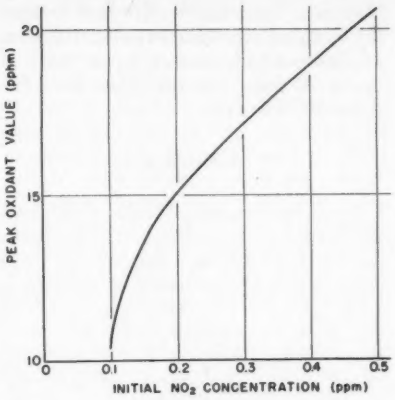

Fig. 11. Effect of initial NO_2 concentration on peak oxidant value.

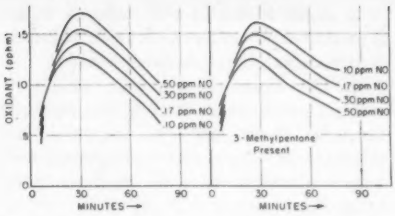

Fig. 12. Interaction between 3-methylpentane and nitric oxide level.

some factor in idling exhaust is more reactive in oxidant formation than the 2 added hydrocarbons, which are believed to be typical of hydrocarbons reaching the air by evaporation.

Effect of Oxides of Nitrogen

1. The peak oxidant value increased as initial NO level was increased (Fig. 10). Similarly, the time required to reach the peak oxidant value increased as the initial NO level was increased.

2. The effect of initial NO_2 level of the peak oxidant value was similar to that of initial NO value (Fig. 11). By comparing the slope of the curves in Fig. 10 and 11, one is struck by the fact that the effect of the initial NO_2 level is much greater than the initial NO level. This would be expected since NO_2 is the light-absorbing agent, whereas NO must first be converted to NO_2 before it becomes activated.

Other Effects

A great many statistically significant relationships of more complex nature were deduced from the data. These serve only to indicate the complexity of the reaction system. Most of these complex relationships involved the runs in which 3-methylpentane was substituted for part of the hydrocarbon content of the idling exhaust. Two of these striking effects are shown in Fig. 8 and 12.

The enhanced activity of 3-methylpentane at low levels of nitrogen oxide concentration suggests that the ratio of the concentrations of hydrocarbon and nitrogen oxides, first mentioned by Haagen-Smit[3] is extremely important in the so-called smog reaction. The optimum ratio may vary so widely from one hydrocarbon type to another that drastic reduction in the level of atmospheric nitrogen oxides may be required to alleviate smog manifestations.

Additional Experiments at Higher Hydrocarbon Concentrations

After the experiment just reported was completed, a similar experiment at higher hydrocarbon concentrations was performed. Four levels of idling exhaust hydrocarbon charge (4.1, 6.8, 12.3, and 20.5 ppm.) were studied; 2 levels of nitric oxide (50 and 100 pphm); and a single NO_2 conceneration (0.225 ppm.). The experiment was a 2 x 4 factorial, replicated twice. A different panel of 10 housewives was used to evaluate eye irritation. Each person entered the chamber 3 times during each experiment.

Again, the degree of eye irritation increased as the initial hydrocarbon level was increased. Contrary to previous experience, the over-all oxidant production *decreased* as the hydrocarbon level was increased. However, the effect of the interaction between nitric oxide level and hydrocarbon level was very pronounced (Fig. 13).

General Conclusions

The following conclusions can be drawn from the data:

1. Auto exhaust, in concentrations similar to those found in the atmosphere, produces both the oxidant and the eye irritation manifestations of Los Angeles smog.

2. Under the experimental conditions employed, eye irritation increased as the hydrocarbon level was increased.

3. Similarly, at hydrocarbon concentrations of the order of those found in the Los Angeles atmosphere, oxidant values increased as the hydrocarbon level was increased.

4. At hydrocarbon levels greater than those found in the atmosphere (but still at experienced nitrogen oxide levels), oxidant formation was suppressed as hydrocarbon concentration was increased. The fact that eye irritation continued to increase at these high levels may be a clue to the anomalies sometimes found between oxidant level and severity of eye irritation.

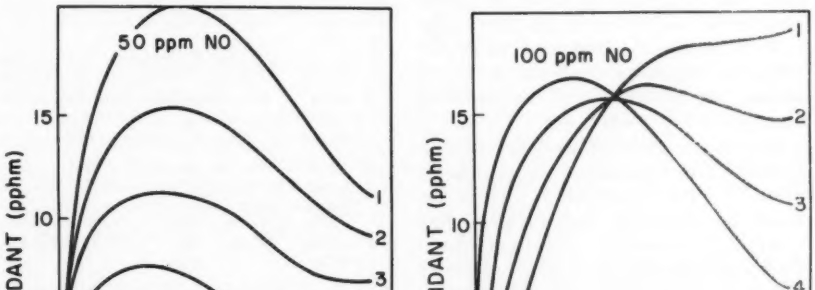

Fig. 13. The effects of the interaction of nitric oxide level and hydrocarbon level on oxidant.

[3] A. J. Haagen-Smit, Chemistry and Physiology of Los Angeles Smog, *Ind. Eng. Chem.* 44, 1342-6 (1952).

5. Some factor in auto exhaust makes it a more potent smog-former than the 2 individual hydrocarbons added.

6. The role of nitrogen oxides in smog formation is a complex one and may be dependent on the type and structure of the organic compound with which it reacts, as well as the concentration ratio.

Future Work

Work done to date on this project has raised many questions that must be answered before a logical solution to the smog problem can be devised. Current work in the facility at Midwest Research Institute is directed toward determining the smog-forming potential of different hydrocarbon types. Work on cycles of auto exhaust other than idle is also under way.

Summary

Hydrocarbons and oxides of nitrogen, in concentrations similar to those found in the Los Angeles atmosphere, were subjected to the influence of sunlight in large glasshouses. Odor, eye irritation, and oxidant concentrations, similar to those of Los Angeles smog, developed in all cases. The sources of hydrocarbons were both auto exhaust and evaporated hydrocarbons.

Eye irritation and oxidant concentration both increased as the concentration of hydrocarbons charged to the chambers was increased. Auto exhaust hydrocarbons were considerably more effective in producing oxidant than were the 2 added hydrocarbons, 3-methylpentane and hexene-1. The effect of oxides of nitrogen concentration was more obscure and complex, but nonetheless important.

It was concluded that automobile exhaust is an important source of smog and must be controlled.

The Chemical and Biological Consideration of Atmospheric Carcinogenic Agents*

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A significant increase in the incidence of cancer of the lung has been reported from various regions of the world during the last 20 to 30 years.[5] This sudden and widespread increase is probably associated with the introduction of carcinogenic agents into the external environment at a time consistent with biological correlation. Of the agents advanced as being causally related to the increase, atmospheric pollution[11] and cigarette smoking[4] have been suggested as the 2 most significant. Since lung cancer in common with all cancers most certainly has multiple factors associated with its initiation and promotion, it appears to us to be an oversimplification to conclude at this time that any single factor is significant to the exclusion of all others. The current report is concerned primarily with the atmosphere as one suggested source of pulmonary carcinogenic agents.

For the sake of clarity, the various known and suspected carcinogenic agents in the atmosphere will at the onset be discussed individually. Any combined or possible inhibitory effects they may possess and their mode of action in relation to the development of cancer will be considered later. A relatively large group of substances strongly suspected as carcinogenic for the lung has already been described. They are being mentioned here for the purpose of completeness as their current significance probably exists only in terms of occupational or localized industrial hazards. Included in this group would be the radioactive dusts and gases[9]; the metal oxide and metal salt dusts and fumes from such elements as chromium[1] and nickel[11]; asbestos[21]; and the organic material, isopropyl oil.[23].

The chemical carcinogens we are primarily concerned with today are those distributed throughout the atmosphere. They fall into 2 groups; polycyclic aromatic hydrocarbons of traditional experimental carcinogenicity and the oxidation products of aliphatic hydrocarbons. The most common source of the former is the exhaust products of internal combustion engines, both gasoline and diesel.[16,17] The latter are derived from unburned gasoline released to the atmosphere incidental to petroleum refining, storage, and distribution as well as from vehicular exhausts.[18] Finally, a group of inorganic dusts will be discussed in relation to a possible role in the pathogenesis of cancer.

A discussion of carcinogenesis should include: 1) consideration of the chemical nature of the suspected or incriminated materials, 2) mechanisms for their deposition on the respiratory epithelium, 3) evaluation of their residence and stability in the respiratory tract and 4) the effect of various agents

(4) R. Doll. Bronchial Carcinoma: Incidence and Actiology. *Brit. M. J.* **23**, 326-342 (1955).
4835:521-537; **4836**, 585-590 (1953).

(5) H. L. Dunn. Lung Cancer in the Twentieth Century. *J. Internat. Coll. Surg.*

*Presented at the American Chemical Society Symposium on Air Pollution at Atlantic City, N. J., Sept. 16-21, 1956.

(1) A. M. Baetjer. Pulmonary Carcinoma in the Chormate Workers. I. A Review of the Literature and Report of the Cases, *A.M.A. Arch. Indust. Hyg. & Occup. Med.* **2**, 487-504 (1950).

(9) F. H. Harting and W. Hesse. Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben, Viertaljahrsschr. *Gerichtl. Med. u. Offentl. Sanitatsw.* (N.S.), **30**, 102-132, 296-309, 1879.

(11) W. C. Hueper. A Quest into Environmental Causes of Cancer of the Lung. *Pub. Health Monograph* **36**, U.S.P.H.S. (1956).

(21) K. Lynch and W. A. Smith. Carcinoma of the Lung in Asbestos-Silicosis, *Am. J. Cancer* **24**, 56-63 (1935).

(23) C. S. Weil, H. F. Smyth, and T. W. Nale. Quest for a Suspected Industrial Carcinogen, *A.M.A. Arch. Indust. Hyg. & Occup. Med.* **5**, 535-547 (1952).

(16) P. Kotin, H. L. Falk and M. Thomas. Aromatic Hydrocarbons II. Presence in the Particulate Phase of Gasoline Engine Exhausts and the Carcinogenicity of Atmospheric Extracts, *A.M.A. Arch. Indust. Hyg. & Occup. Med.*, **9**, 164-177 (1954).

(17) P. Kotin, H. L. Falk and M. Thomas. Aromatic Hydrocarbons III. Presence in the Particulate Phase of Diesel Engine Exhausts and the Carcinogenicity of Exhaust Extracts. *A.M.A. Arch. Indust. Health* 11, 113-120 (1955).

(18) P. Kotin, H. L. Falk, and M. Thomas. Production of Skin Tumors in Mice with Oxidation Products of Aliphatic Hydrocarbons. *Cancer* (in press).

upon the epithelium *per se* as well as upon one another. Incidental mention will be made of the possible contribution of cigarette smoke in the enhancement of the carcinogenic effect of air pollutants.

The aromatic polycyclic hydrocarbons with carcinogenic potency have been the subject of long and intensive study. Their universality in the atmosphere has been reported by investigators in Great Britain[22] as well as by ourselves.[15] The most potent of these compounds is 3,4-benzpyrene. It may be accompanied by other organic compounds, a few of them showing weak activity as, for example, chrysene. Soot is the most ubiquitous carrier of these carcinogenic agents. A strong likelihood exists that other potent aromatic polycyclic carcinogens of the 1,2-benzanthracene type as present in tar fumes or road asphalt dust may be of etiologic significance[2] The experimental carcinogenicity of the polycyclic aromatic compounds has been demonstrated following their recovery from the atmosphere.[3, 19, 20]

Carcinogenicity has also been demonstrated in atmospheric samples either free of aromatic polycyclic hydrocarbons or samples in which their concentration is so low as to be presumably free of responsibility for tumor production of these samples.[13] The presence of this second group of compounds belonging to the aliphatic hydrocarbon group has been postulated as being responsible for the carcinogenicity in the polycyclic aromatic-free samples. While this group of compounds is much less well defined chemically, their mode of formation can be outlined. The exposure of gasoline in low concentration to ozone results in the formation of an aerosol with marked oxidizing power. The chemical reactions responsible can be theoretically elucidated. The degree to which the various groups of resulting compounds are formed and to what extent they survive in the atmosphere is not known. Suffice it to say that the reaction occurs exceedingly rapidly and the products contain a variety of oxidants. To a limited degree these have been separated by distillation, chromatography, and standard chemical means. Ozonides, peroxides, peracids, peresters, and end products consisting of aldehydes, ketones, acids, and epoxides probably result from this reaction[12] A complex mixture of these compounds is obtained even following the initiation of the reaction using pure 2-hexene and ozone under laboratory conditions. The complexity of the reaction products is undoubtedly formidably increased when one considers the variety of compounds emitted from vehicular exhausts. This coupled with the instability, explosive nature, and low concentration of the oxidation reaction products makes large scale bioassay for carcinogenicity impractical at present. Consequently, compounds considered to be structurally similar to the reaction products have been chosen for carcinogenic studies. These are more easily obtainable and their purity can be established.

Prior to discussing biological data obtained from carcinogenic studies, it will be profitable to discuss the problems inherent in the testing of compounds or groups of compounds for carcinogenicity. Choice had to be made of the species to be tested, the target tissue, the mode of administration, the dose of the carcinogen, its vehicle, and the duration of experimental time. With current interest centered primarily around lung cancer, the tissue selection appears obvious, that is, the lung. Experimental considerations, however, made it much more expedient to begin with skin painting and subcutaneous injection techniques using mice and rate as the species. This permitted the accumulation of knowledge relative to the toxicity, stability, and the host's reaction to the administered compounds. Following the demonstration of skin carcinogenicity, using extracts of soot from diesel engine exhaust, gasoline engine exhaust, and polluted air, a series of experiments were undertaken using various fractions of these materials for the purpose of identifying specific carcinogens and measuring relative potencies. Only subsequent to these basic experimental endeavors was it expedient to perform inhalation experiments using the lung *per se* as the target tissue. This experimental sequence has been followed through to completion in the instance of aliphatic oxidation products[14] and is in the process of completion utilizing aromatic polycyclic hydrocarbons.

Although data relating to the phenomenon of lung cancer as currently occurring in humans may be only inferentially studied in experimental species, we have by means of experimental methods through data obtained in our laboratory evolved a theoretical mechanism for pulmonary carcinogenicity in man. This necessitates a consideration not only of the carcinogenic agents *per set* but other environmental factors which adversely affect the respiratory epithelium so that carcinogenic activity may result.

The demonstration of carcinogenic materials in the atmosphere required investigation as to their quantitative presence, stability, survival time, and physical state. Representative studies have shown that the polycyclic aromatic hydrocarbon carcinogen, 3, 4-benzpyrene absorbed on soot, is relatively stable when compared to pyrene and other polycyclic hydrocarbons. It is slowly destroyed, however, by polluted air rich in oxidants. The survival time is, however, wholly compatible with respiration and deposition in the lung.[7]

The oxidant material in the atmosphere in addition to the innate carcinogenicity already discussed possesses the property of extracting the aromatic carcinogen from the soot onto which it is normally absorbed. This elutant prop-

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(2) J. A. Campbell. Cancer of the Skin and Increase in Incidence of Primary Tumours of Lung in Mice Exposed to Dust Obtained from Tarred Roads. *Brit. J. Exper. Path.* **15**, 287-294 (1934).

(3) G. R. Clemo and E. W. Miller. The Carcinogenic Action of City Smoke. *Chem. & Ind.*, p. 38 (1955).

(13) P. Kotin and H. L. Falk. Production of Tumors in C57 Black Mice with Atmosphere Extracted Aliphatic Hydrocarbons. *Proc. Am. Assoc. Cancer Research,* **2**(1), 30 (1955).

(15) P. Kotin, H. L. Falk, and M. Thomas. Aromatic Hydrocarbons I. Presence in the Los Angeles Atmosphere and the Carcinogenicity of Atmospheric Extracts, *A.M.A. Arch. Indust. Hyg. & Occup. Med.* **9**, 153-163 (1954).

(19) J. Leiter and M. J. Shear. Production of Tumors in Mice with Tars from City Air Dusts. *J. Nat. Cancer Inst.* **3**, 167-174 (1942).

(20) J. Leiter, M. B. Shinkin, and M. J. Shear. Production of Subcutaneous Sarcomas in Mice with Tars Extracted from Atmospheric Dusts, *J. Nat. Cancer Inst.* **3**, 155-165 (1942).

(22) R. E. Waller. The Benzpyrene Content of Town Air, *Brit. J. Cancer.* **6**, 8-21 (1952).

(12) P. Kotin. The Role of Atmospheric Pollution in the Pathogenesis of Pulmonary Cancer: A Review. *Cancer Research* **16**, 375-393 (1956).

(7) H. L. Falk; I. Merkul; and P. Kotkin, Aromatic Hydrocarbons IV. Their Fate Following Emission into the Atmosphere and Experimental Exposure to Washed Air and Synthetic Smog. *A.M.A. Arch. Indust. Health,* **13**, 13-17 (1956).

(14) P. Kotin and H. L. Falk. The Experimental Induction of Pulmonary Tumors in Strain A Mice Following Their Exposure to an Atmosphere of Ozonized Gasoline. *Cancer* (in press).

erty is of great significance in that it has been previously shown that carcinogenic agents during the state of their adsorption on soot are biologically ineffective.[8] At this time it is well to mention that other factors highly capable of being associated with the elution of hydrocarbons from soot are present in our environment. The one in need of great study and worthy of suggestion is cigarette smoke.

Studies by our group and others [12, 10] on the various aspects of air pollution have demonstrated the role of ciliary activity and bronchial mucus secretion as protective factors for the respiratory epithelium. This defense mechanism is operative primarily against inhaled particulate matter. The preponderance ot inhaled particulate matter has been shown to be in the particle size range which allows for passage through the nares, the trachea, and the major bronchi with deposition in the smaller bronchi, bronchioles, and alveoli. Particulate matter is then either phagocytized and adsorbed or removed by ciliary action. Studies on human lungs obtained from necropsy reveal that in the instance of soot, approximately 1% of the total amount inhaled during life is retained in the lungs and lymph nodes.[6] Chemical analysis of this soot by ourselves revealed it to be almost entirely free of carcinogenic aromatic polycyclic hydrocarbons. Only minute amounts of pyrene were detectable in all of the lungs studied. This disappearance of the carcinogenic agents suggests that the adsorption bond between them and the soot may have been broken as a result of elutant activity. Whether the liberated carcinogen is harmlessly destroyed or whether it mediates a carcinogenic effect is now under intensive study in our laboratory.

Ciliary movement in association with the mucus barrier serves to remove particulate matter which has been deposited on the lining of the lung. This material is progressively advanced towards the throat region where it is either expectorated or, as is more frequent, swallowed. As mentioned previously, the role of aliphatic oxidation products in the interference with the normal resistance factors of the respiratory epithelium must be regarded in evolving a sequence of lung cancer development. Any interference with these defensive factors reduces ciliary activity and results in extended residence time of particulate matter on the epithelium. This allows for prolonged direct chemical action on the cells *per se.*

Experimentally, this was demonstrated in rabbits that were exposed to synthetic smog of from 1-3 ppm. for periods of from one hr. to several days. Ciliary activity was observed and quantitated, using a dissecting microscope in isolated strips of trachea. Particles used for study were in the size range of 500 mm. Control animals showed a relatively constant rate with particle movement measuring 10 mm./min. In all animals exposed to smog prior to tracheal exteriorization the rate of particle movement was considerably reduced. Smog exposure for 24 hr. completely abolished ciliary activity and particle movement. Measurement of recovery rate as determined by ciliary activity or particle size movement showed a restoration to levels of 35% of normal in 48 hr. after cessation of ciliary activity.

The effect of aliphatic oxidation products on the mucus barrier is equally dramatic. A gradual increase in goblet cell activity and mucus secretion occurs to the point where pools or lakes of mucus form. Following this, there is desquamation of the superficial epithelial cells with the resultant exposure of the basal cell layer. This cell layer from which lung cancer presumably originates is then unprotected and carcinogenic agents present and available for biological activity are immediately adjacent to their target. The persistance of the basal cell layer is of further significance in that it allows for restoration of the epithelium following the removal of the irritants. Epithelial replacement is complete with no discernible evidence of prior loss.

Prior to concluding, brief mention of the possible role of inorganic dusts should be made. The stimulating effect of such agents as silica, alumina, and iron oxide on connective tissue proliferation is well known. The recent production of sarcomas by the instillation of these materials in the mesenchyme of experimental species indicates a need for their evaluation as either additive or potentiating agents when associated with other known atmospheric carcinogens.

In conclusion, a review of the factors relating atmospheric pollution to lung cancer strongly suggests that it be regarded as one of the agents etiologically associated with the increase in mortality from lung cancer now being recorded throughout the world. Lung cancer in common with all other neoplasms must certainly have many factors concerned with its initiation and promotion. While the relative significance of these various factors is at present the subject of great controversy, epidemiologic and experimental data obtained from broad programs of lung cancer research strongly support the thesis that air pollution provides a source for agents carcinogenic to the lung. Chemically, carcinogenic agents have been demonstrated in the atmospheric environment, and biologically, a mechanism utilizing laboratory data has been advanced for the pathogenesis of lung cancer. This report certainly does not preclude possible similar roles by other environmental factors.

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(6) H. L. Falk and P. Kotkin. The Fate of Polycyclic Aromatic Hydrocarbons in Soot Following Their Emission into the Atmosphere and Deposition in the Lungs. *Proc. Am. Assoc. Cancer Research* **2** (1): 15, 1955.

(8) H. L. Falk and P. E. Steiner. The Identification of Aromatic Polycyclic Hydrocarbons in Carbon Blacks. *Cancer Research* **12**, 30-9 (1952).

(10) A. C. Hilding. On Cigarette Smoking, Bronchial Carcinoma and Ciliary Action II. Experimental Study on the Filtering Action of Cow's Lungs, the Deposition of Tar in the Bronchial Tree and Removal by Ciliary Action. *New England J. Med.* **254**, 1155-1160 1155-1160 (1956).

Removal of Bacteria from Air Streams by Glass Fiber Filters*

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There are now commercially available highly efficient mechanical air filters. These may be substituted for expensive air cleaning systems in most industrial organizations, research institutions, and hospitals which require bacterial free air in the inlet air distribution systems as well as safe disposal of contaminated air.

Current Developments

A glass fiber filter paper originally developed jointly by the Department of the Navy and the National Bureau of Standards is now being produced commercially. This filter medium is as thin as coarse paper (10 mils) and is comprised of glass fibers 0.5 to 0.75μ in diam.

Bacteriological arrestance tests have been conducted on this type of paper when fabricated into a filter unit of 50 cfm. capacity and capable of withstanding temperatures up to 1000°F. The one outstanding feature of this unit is the compatability of materials. The frame, gasket and filter medium were made from identical basic materials, and will react the same to temperature changes.

Test Procedures for Evaluation of Glass Paper Filter Unit

A bacterial suspension of *Bacillus subtilis var. niger*, frequently referred to as *Bacillus globigii*, was used to evaluate the efficiency of the filter. The size of the organisms is 0.5 by 1.0 to 1.5μ. The organisms were nebulized into a cloud chamber by means of an all-glass direct spray peripheral air jet atomizer. Biological material from this nebulizer is not always unicellular because agglomeration may occur during or after release of the aerosol. The cloud of bacteria was mixed with air, then passed to a pre-filter chamber, through the filter medium at a face velocity of 5 ft. min., onto a post filter sampling chamber and finally exhausted by means of a blower to the outside air.

Results of a series of 11 tests conducted over a 66-hr. test period are recorded in Table I. The average percent penetration during the first hr. of the test period was 6.7×10^{-6}% and decreased to 7.0×10^{-7} % after a 66-hr. period. It should be noted that there was considerable variation within this penetration range. This is accounted for by the fact that the filtration efficiency was so high that the post filter collection of a few organisms would greatly magnify the aerosol penetration in such a low order of leakages. It also should be noted that penetration of the test organisms through the filter decreased with use and was less than 1/100 million at the completion of the test.

Use of Spun Glass Pads In Air Purification Systems

Organizations interested in biological filtration systems that have efficiencies of approximately 99% filtration may use a system employing spun glass pads. A series of tests evaluating the bacterial arrestance of spun glass pads 0.5 in. thick, and having fiber diam. of approximately 1.25μ, has been reported previously by Decker and co-workers in scientific journals.[1,2] These spun glass pads were installed in a filter unit containing wedge shaped pockets supported in a grid type frame. Each frame could hold 1 to 5 pockets. In the standard type frame holding 5 pockets the total net filtering area was approximately 50 ft.[2] and the normal capacity was 1000 cfm. In these tests on spun glass pads, *Serratia indica* was used; however, the method of aerosol generation as well as the particle size were approximately the same. The results of 45 tests showed an arrestance of 99% when evaluated at the normal filter capacity.

Summary and Conclusions

Spun glass pads are satisfactory in all ordinary situations found in hospitals and industrial concerns. In ex-

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-4, 1956.

[1] H. M. Decker, F. A. Geile, H. E. Moorman and C. A. Glick. Removal of Bacteria and Bacteriophage from the Air by Electrostatic Precipitators and Spun Glass Filter Pads. *Heating, Piping, Air Cond.* ASHVE Journal Section 23, 125-9 (Oct. 1951).

[2] H. M. Decker, J. B. Harstad, F. J. Piper and M. E. Wilson. Filtration of Microorganisms from Air by Glass Fiber Media. *Heating, Piping, Air Cond.* ASHVE Journal Section 26, 155-8 (May 1954).

TABLE I

Penetration of *Bacillus Subtilis Var. Niger* Spores Through Commercially Produced High Temperature All-Glass Filter Unit

Test No.	No. organisms collected ft³ air before filter	Duration of test No. hrs. test	Cuml. hrs.	Total airflow, ft³	% penetration during test interval
	x 10^5				
1	40.4	3	3	5,400	6.7×10^{-6}
2	67.3	6	9	16,200	2.1×10^{-6}
3	60.0	6	15	27,000	1.6×10^{-5}
4	102.3	6	21	37,800	1.1×10^{-5}
5	114.3	3	24	43,200	5.7×10^{-6}
6	59.9	6	30	54,000	6.2×10^{-6}
7	106.0	6	36	64,800	3.5×10^{-6}
8	58.7	6	42	75,600	1.7×10^{-6}
9	33.9	6	48	86,400	1.9×10^{-6}
10	13.4	6	54	97,200	2.1×10^{-6}
11	51.7	12	66	118,800	7.0×10^{-7}

Note: Airflow, 50 cfm.

tremely specialized circumstances, as in the case of some research institutions where unusual number of disease producing organisms are handled in large numbers and accidentally or deliberately released into the air, incineration or use of glass paper filters is recommended. Where the dust content of the atmosphere is high, pre-filters are recommended to provide longer life to the more efficient filter systems. However, it should be realized that pre-filters are of very little value for the removal of airborne biological particulates.

In addition to the use of efficient biological air filtration systems in certain critical areas or hospitals and research centers, consideration must be given to the type of air pressurization systems which must be maintained if a satisfactory biological free condition is to be achieved. If it is desired to keep the room atmosphere free of biological organisms, which is a condition desired in hospital operating rooms, then it is necessary to keep that room at a higher pressure than the surrounding rooms. On the other hand, if one is working in a room with pathogenic bacteria, then it becomes desirable to have that room under negative pressure so that airflow is through the exhaust filtration system and not spread through the other areas.

Airborne Microorganisms as Analytical Tools in Aerosol Studies*

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During the past several years, the entire effort of the Aerobiology Laboratory and much of that of the Micromeritics Laboratory of the Georgia Institute of Technology has been devoted to studies on the fundamental nature and behavior of living airborne bacteria. As a direct result of these studies [1], it has been discovered that airborne microorganisms are themselves a valuable tool for the study of many kinds of aerosols, and that, through their use, numerous characteristics of aerosols can be determined with a high degree of accuracy.

The use of microorganisms for the assay of antibiotics, vitamins, amino acids, and enzymes has been well established [2], and the various advantages inherent in their application to analytical chemistry, as well as the nature of the responses involved in these applications have been thoroughly explored [3]. Pure cultures of authenticated strains of various organisms can be obtained from the American Type Culture Collection, thus making possible the universal application of such methods with the assurance of common responses. Bacteria are easily grown, and, with reasonable precautions, identical strains will yield consistent results in various laboratories, year in and year out. For the assay of various compounds, reproducibilities of $\pm 5\%$ are generally reported [2].

It should be pointed out that the greatest difference between an assay using microorganisms and one using chemical or instrumental methods is the time factor. With a chemical or instrumental method considerable time may be required of the operator during the course of the assay, but ordinarily, the results are immediately available. However, with assays using microorganisms, once the assay has been started, no time or effort on the part of the operator is required, although a time lapse of 1 to 2 days is required before the results can be obtained. This is due to the time required for the microorganisms to grow and repoduce. In the well organized laboratory this time lapse is used to good advantage for the taking of earlier results and the preparation for subsequent assays.

It is the process of growth and reproduction that makes microorganisms such an excellent particulate tool in aerosol studies. A single airborne microorganism settling upon a nutritive surface will, in a period of 12 to 24 hr., grow and multiply until a colony is formed. This colony, representing one single original particle, is readily visible to the unaided eye, although ordinarily counted with the aid of 2x lens. The same state of affairs exists for airborne microorganisms sampled directly from the air, where each single particle can be counted if desired. With the possible exception of certain *particle counters* [4,5] there is no other known method whereby individual particles can be counted and their distribution determined with so little time and effort on the part of the operator as is the case with living airborne microorganisms.

Bacteria are the most useful of the various microorganisms in aerosol studies, although bacteriophages, viruses, and mold spores can be used to advantage in certain studies. Bacteria are small, single-cell organisms classified as members of the plant kingdom. The physical and chemical cultural requirements of these organisms are relatively more simple and amenable to control than are animal cells as seen in tissue culture. For those bacteria most often used in aerosol studies, the cultural requirements and techniques are reasonably well established. Standard commercially available culture media further enable uniformity of results from testing procedures.

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[1] J. M. DallaValle, T. W. Kethley, W. B. Cown, and E. L. Fincher. *Final Report G-2771, An Investigation of the Effect of Minute Quantities of Chemical Vapors on Airborne Bacteria.* National Institutes of Health, United States Public Health Service, Jan. 1956.

[2] D. A. Harris, *Anal. Chem.*, **27**, 1690 (1955).

[3] B. C. Knight, J. G., *et al.*, *Biochem. J.* (London), **41**, i (1947).

*Presented at the American Chemical Society Symposium on Air Pollution at Atlantic City, N. J., Sept. 16-21, 1956.

[4] F. T. Gucker, Jr. and C. T. O'Konski, *Chem. Rev.*, **44**, 373 (1949).

[5] N. E. Alexander, *Chem. Eng. News*, **33**, 1083 (1955).

A general morphological scheme classifies bacterial cells into 3 groups: the round (*cocci*), rod-shaped (*bacilli*), and helicoid (*spirochetes, spirilli*). The size variation in bacterial cells is from slightly less than 0.5μ in diam. to rods as long as 200-500μ. The selection of a bacterial genus and species for production of an aerosol would be restricted ordinarily to the round (*cocci*) or short rod-shaped (*bacilli*) organisms in the size range of 0.5 to 3.0μ. Even smaller initial particles could be produced from a bacteriophage such as the T-3 strain of *Escherichia coli*. These viral bodies are in the range 0.02 to 0.05μ.

All bacteria exist in what is termed the vegetative form, in which growth and reproductive activities take place. In addition to this form, some bacteria are capable of developing into a physiologically dormant form called a spore. In this state, the organism is extremely resistant to environmental conditions, which in the active vegetative state would be very adverse to continuing life. This resistance is unequalled by any other living thing [6]. Under proper conditions the spore will germinate into the actively growing and reproductive vegetative state. These characteristics of an organism in the spore state make such an organism exceptionally useful in aerosol work under a very wide range of conditions.

The bacteria commonly used in aerosol studies, such as *Serratia marcescens, S. indica, Escherichia coli*, and the spore formers *Bacillus subtilis morphotype globigii* (*B. globigii*), and *B. cereus*, are classified as nonpathogenic, *i.e.*, nonproductive of disease in man. In addition to the nonhazardous use of such organisms, their use is facilitated by relatively simple nutrient and cultural requirements for growth.

For aerosol studies bacteria are easily grown in liquid or on solid media. The vegetative form of bacteria grown on a solid medium may be *harvested* and put into a suitable aqueous suspension for use in aerial dispersion. For subsequent use, the vegetative cell may be suspended in an appropriate aqueous suspension for freeze-drying[7]. Such frozen-dried organisms may be dispersed as dried particulates or resuspended in a liquid medium. Spores may be managed more directly from growth on a solid medium both as dried spores or as a spore suspension in an aqueous medium. The dried spores in a desiccated atmosphere and the spore suspension under refrigeration (6-10° C.) will show inappreciable variation in numbers during months of storage [8].

TABLE I

Experimental and Calculated Particle Diameters Using Various Dispersion Media

(All other Operating Conditions Identical)*

Composition of Dispersion Fluid	Experimentally Determined Particle Diam.	Calculated Particle Diam.	Relative Humidity at which Observations Were Made
	(microns)	(microns)	
0.375% Glycerol in water	2.24	2.14	45
	2.58	2.55	80
0.1% NaCl added to 0.3% Beef Extract Solids	1.89	1.96	25
	2.64	2.70	80
0.3% Beef Extract Solids	1.8	1.80	20
	2.0	1.85	40
	2.1	2.0	60
	2.5	2.5	90
Pure Water	0.61	0.7	16
	0.56	0.7	25
	0.64	0.7	60

*All experimental determinations were made from viability data; essentially single-bacterium particles were used. Calculated particle sizes were based on 13μ diam. original droplet and equilibrium moisture characteristics of the low vapor pressure materials in the dispersion fluid. The equivalent diam. of the bacterial cell is only 0.7μ, and represents a negligible portion of the particle. DeVilbiss No. 40 all glass atomizer, 6.40 L./min. was used. Dispersion fluid was held at 10° C.; all observations were made at 20° C.

Evaluation of Atomizer and Sprayer Performance

The formation of aerosols for a variety of purposes—from spray drying to insect killing—is carried out by the formation of initial droplets of the dispersion fluid, in which the solids are dissolved. The evaporation of the liquid portion of the dispersion fluid leaves the dissolved solids suspended in the air as small particles of matter. The formation of the initial droplet is usually by a shearing action, which probably sets the lower limit of the droplet size as 10μ diam. [9]. Consideration of the evaporation from small spheres [10, 11], shows that droplets of water as large as 50μ in diam. will evaporate in approximately 1 sec. in dry air. This fact accounts for the success of many spray drying operations, and illustrates the rapidity with which *atomized* droplets will evaporate. The concentration effect of such evaporation is tremendous. For example, a 50μ diam. droplet containing 1% dissolved solids would result in a 10.7μ diam. particle of solid matter, if there were no interaction between the vapor content of the surrounding air and the solid matter of the particle. However, there is such interaction for most materials; various crystalloids form solutions with the water of the atmosphere, non-crystalloids exhibit various affinities for the moisture in the atmosphere.

As a result of the interaction between atmospheric vapors and the various materials composing the low vapor pressure residues of droplets produced by atomizing or spraying, it is often difficult to determine the exact size of the initial droplets produced, or the size of the residual particles formed by these processes. The introduction of a formed body as a *tracer* greatly facilitates such studies. Living bacteria, either spores or vegatative forms, are exceedingly useful for this purpose, because the size of the residual particles can be determined directly under the various conditions of relative humidity without requiring any intermediate steps which might introduce errors due to change in the water content of the particle. The size of the bacterial cell will vary only slightly with changes in humidity [12], and will introduce a negligible change in the overall particle size. Bacteria are most conveniently used in a dynamic aerosol chamber such as described by this group[1, 13] in which aerial and settling samples are taken simultaneously. For such work, particles principally carrying a single bacterium can readily be obtained by properly adjusting the concentration of organisms in the original aqueous suspension[1,14].

Illustrative data are shown in Table I for the calculated and determined

(6) H. R. Curran, *Bacteriol. Rev.* **16**, 111 (1952).

(7) H. B. Naylor and P. A. Smith, *J. Bacteriol.*, **52**, 565 (1946).

(8) M. Levine, *Bacteriol. Rev.* **16**, 117 (1952).

(9) R. A. Castleman, Jr., *Bur. Standards J. Research*, **6**, 369 (1931).

(10) I. Langmuir, Phys. Rev., **12**, 368 (1918).

(11) H. G. Houghton, *Physics*, **4**, 419 (1933).

(12) C. Orr, Jr., and M. T. Gordon, *J. Bacteriol.*, **71**, 315 (1956).

(1) See footnote 1, Page 16.

(13) T. W. Kethley, W. B. Cown, and E. L. Fincher, The Nature and Composition of Experimental Bacterial Aerosols. *Appl. Microbiol.* (Jan. 1957).

(14) , E. L. Fincher and W. B. Cown, *Appl. Microbiol.*, **4**, 237 (1956).

TABLE II

The Detection of Inhomogeneity In A Dilute Aerosol With Airborne Bacteria

Conditions of Experiment	Aerial Concentration Viable Organisms L.		Range of Counts Expected on Settling Plates	Range of Counts Observed on Settling Plates		
				Range of Counts	Incidence of Counts	% of Total
	Average	S.E.				
Cells dispersed from Beef broth, 40% Relative Humidity	1500	50	59-72*	35-55 56-75 76-96	12 41 7	20 69 11
Cells dispersed from Beef broth, 0.1% NaCl added, 25% Relative Humidity	7500	250	286-350*	211-280 281-350 351-420	2 22 5	7 76 17
Cells dispersed from 0.375% glycerol in water, 40% Relative Humidity	3100	70	168-210*	116-165 166-215 216-265	4 21 4	14 72 14
Cells dispersed from pure water, 16% Relative Humidity	2200	80	74-92**	1-20 21-45 46-70 71-95 96-120 121-145 146-170 171-400	8 5 6 12 2 5 0 10	17 11 12 25 4 11 0 20
Cells dispersed from pure water, metal premix, and chamber grounded, 16% Relative Humidity	1600	53	42-51**	1-20 21-40 41-50 51-60	5 2 7 1	33 13 47 7

*Settling plates exposed for 1 min. intervals.
**Settling plates exposed for 5 min. intervals.

particles produced from several different dispersion media, under identical conditions. Except in the case of pure water, the content of the medium was chosen to yield particles of essentially identical size under identical conditions. Such an approach is readily applied to the study of other concentrations, and other operating conditions of the atomizer or sprayer.

Determination of the Homogeneity of Dispersion of Aerosols

Another phase of aerosol studies which can be attacked conveniently with airborne organisms relates to the estimation of the homogeneity of dispersion of aerosol clouds, especially very dilute ones. As stated before, the advantage of using viability determinations is that it is possible to count each particle. Furthermore, it is possible to determine the exact location where it fell. In practice, we have made studies in a 4-ft. cubical chamber, [1,13] having 4 settling plate holders located equidistantly across one diagonal of the floor. With these plate holders it is possible to expose agar plates at the floor level for any desired period of time, and then remove them, replace them with fresh plates, all without disturbing the operation of the chamber. In making our studies on airborne washed cells, dispersed from pure water (and therefore with no adherent materials), we observed that the settling plates showed either crowded spots of colonies, or virtually no colonies at all. This was in strong contrast to the results obtained with airborne organisms dispersed from fluids containing various solids. In these instances, the settled colonies had been uniformly distributed over each exposed plate, and good agreement existed between simultaneously exposed plates for the various plate positions.

In the case of the airborne washed cells, further study showed that the only logical explanation of the peculiar settling pattern was that there were small groups of a few hundred airborne particles which were hanging together despite all efforts to disperse them. The number involved in each little concentrated cloud could not be very great because the samples taken from the air had indicated no unusual distribution within the chamber. However, the aerial samples consisted of several thousand airborne particles, while the settling samples demonstrated each individual particle.

Further investigation showed that the aerosol cloud formed by the washed cells exhibited a uniformly balanced charge picture, whereas the other clouds tested showed a definite imbalance of charge. This fitted previous observations where it had been found that clouds having no excess of charges were extremely difficult to disperse, and those having definite excess charge were relatively easily dispersed. A study of the pattern obtained from the settling plates verified this. Of all the airborne particles thus far studied, only those of the washed cells have shown such irregular settling patterns, and these have been the only ones which as a cloud exhibited no net charge.

The results of certain of these studies are shown in Table II. It thus became apparent that the study of settling patterns offers a useful method for determining directly the minute-to-minute distribution of particles in dilute aerosol clouds. Such a method is particularly applicable to the study of various methods for attempting the uniform dilution of aerosol clouds for laboratory studies.

Determination of Arrester Efficiencies

Drinker [15] first suggested the use of pollens for testing and rating air filters. Pollens are particularly uniform in size, disperse easily and are readily identified. However, most available pollens are greater than 10μ in diam. and are relatively costly. While it is true that they are easily identifiable, techniques for capturing them on the upstream and downstream sides of a filter undergoing test leave much to be desired. It is also possible that arrester efficiencies determined by use of pollens are higher than they should be, due both to their larger dimensions and to their surface characteristics which tend to make them readily captured.

DallaValle and Hollaender [16] first proposed the use of a microorganism (*B. subtilis*) as a method for testing air filters and other forms of arresters. Surprisingly good results were obtained, consistent with those obtained by more refined methods. The *B. subtilis* spore is highly resistant and small enough to compare favorably with dusts and aerosols usually encountered in city air. Table III shows some results of the 1939 study.

[1] See footnote 1, Page 16.
[13] See footnote 13, Page 17.

[15] P. Drinker and W. F. Wells, *Journal Section, Heating, Piping Air Conditioning*, 6, 408 (1934).
[16] J. M. DallaValle and A. Hollaender, *Public Health Repts., (U.S.)*, 54, 695 (1939).

More recently Humphrey and Gaden [17] reviewed the use of microorganisms in the evaluation of filters and reported on the collection effectiveness of fibrous media, using spores of the same organism, *B. subtilis*. These workers obtained a uniform dispersion of particles 0.6μ in radius, using very simple procedures. Considering the usual difficulties of preparing synthetic dusts for testing purposes, especially as regards particle size distribution and aggregation, there are many advantages to the use of microorganisms in such evaluation studies.

It might be mentioned that the chief criticism against the use of synthetic dusts and the current methods of rating most commercial arresters is that efficiencies are on a weight basis. This requires loadings of filters far in excess of those concentrations normally found in city air. Thus, it is not an initial concentration that is determined, but an average of an integrated efficiency. Many filters are notoriously inefficient until used for a period of time. In addition, weight methods of rating arresters overlook the fact that particle volume (and hence the mass) varies as the cube of dimension. A few large particles, which are easily captured, may far outweigh many millions of smaller ones which get through. The use of a uniform material such as a dispersion of microorganisms eliminates both objections.

Evaluation of Sampling Devices

Extremely small quantities of microorganisms can be detected by proper culturing techniques and somewhat monodispersed aerosols can be obtained without undue difficulty [1,14]. Aerosols in a variety of particle sizes can be obtained by selecting the appropriate microorganism; furthermore, some variation in particle size can be achieved by the use of dispersing fluids of varying compositions. The effect of relative humidity on particle size has already been indicated (Table I). For these reasons microorganism aerosols make very satisfactory tools for comparing the efficiencies of sampling devices, for calibrating them and for making a variety of studies with them[1]. In addition to the great number of purely comparative studies to be found in the literature, living cells have been employed in certain definitive studies. For example, thermal precipitation

TABLE III

Efficiencies of Certain Types of Commercial Air Filters Against Bacteria *Bacillus subtilis* Filtration Velocities 1000 lfm

Type of Medium	Efficiency
Felt Cloth	63.5±6.5
X-ply Paper	74.8±5.6
Steel Wool (oil coated)	82.9±7.6
Glass Fabric	32.6±8.3

was compared with liquid inertial separators using *S. marceseens* and *B. subtilis* by Orr, Gordon and Kordecki[18], Watson[19], used spores in his study of isokinetic sampling; Farlow and French[20] used corn smut spores in calibrating liquid aerosol collectors. Whenever a detector for fine particles is to be tested, microorganisms offer advantages over many other aerosols, both as formed bodies and as living cells.

Application to the Detection of Trace Vapors and Gases

The wide range of viabilities with different species of microorganisms renders them especially useful as enviromental indices. Their usefulness in this connection has long been recognized in public health work, especially in water purification and treatment and in testing disinfectants. Many organisms are known to be affected in certain ways by different liquid or gaseous substances and in varying degrees of concentrations. Such effects were well-demonstrated by DallaValle, *et al* [1] in the investigation of the effects of certain vapors and gases on the airborne organism, *S. marcescens*. This study indicates that airborne microorganisms can be used as detectors of gaseous air pollutants at concentrations far below those detectable by usual sampling procedures.

The use of dispersing fluids of various composition can extend the usefulness of microorganisms in the detection of trace vapors and gases. It has been shown by this group [13,14] that the solids from the dispersion fluids make up the immediate environment of the airborne organism. When materials are used in which the suspect vapor is highly soluble, the organisms are rendered even more sensitive to the vapor through the concentration of the vapor by condensation and solution. In this manner vapor concentrations well below saturation can effect relatively high concentrations in the airborne particle and cause an increased death rate among the microorganisms.

Ventilation and Meteorological Applications

Dalla Valle and Hollaender [21] showed that microorganisms could be used successfully in tracing the flow of air in a ventilating system in which recirculation was varied. This procedure can be extremely useful in mapping flow patterns in ventilated enclosures, especially where very low flow rates are encountered. The same technique suggests itself in studying the distribution of pollutants downwind from a stack at any desired level. In many studies of stack emission where fine particles are concerned, local turbulence at ground level can materially affect sampling results. The use of microorganisms which are not indigenous to the locale or which are not normally present in the air in significant numbers can be effective in gaging downwind concentration of particulate matter, especially in the particle size range of greatest interest. Thus, the use of this method suggests itself strongly as a means of surveying the possible distribution of pollutants from a stack prior to its construction. Such a method is much needed in current studies. Its ease of application and certainty of results once obtained renders the method a powerful tool in air pollution surveys.

Suggested Applications

In addition to the proven usefulness of microorganisms as tools in the aerosol studies cited herein, other applications can be suggested which, to our knowledge, have not been tested. Certain forms of microorganisms might be

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(1) See footnote 1, Page 16.

(14) See footnote 14, Page 17.

(17) A. E. Humphrey and E. L. Gaden, Jr., *Ind. Eng. Chem.*, 47, 924 (1955).

(18) C. Orr, Jr., M. T. Gordon, and M. C. Kordecki, *Appl. Microbiol.*, 4, 116 (1956).

(19) H. H. Watson, Errors Due to Anisokinetic Sampling of Aerosols. p. 31, Report of Symposium V, Aerosols, Army Chemical Center, Maryland (1953).

(20) N. H. Farlow and F. A. French. *J. Colloid Sci.*, 11, 177 (1956).

(13) See footnote 13, Page 17.

(14) See footnote 14, Page 17.

(21) J. M. DallaValle and A. Hollaender, *Public Health Reports (U.S.)*, 55, 1268 (1940).

useful in studies on the coagulation of dilute aerosols. In this instance they might be employed either as uniformly formed bodies, the incidence of coagulation being indicated by the increase in numbers per particle, or the distinction might be made through viability determination by the use of differential sampling. In the latter instance, the numbers of particles could be determined from settling plate data and the total numbers from liquid samplers; the average number per particle could then be calculated.

Microorganisms, because of their size uniformity, might also be employed in light scattering studies. They might prove useful in evaporation and condensation investigations; with them rate of evaporation and condensation might be investigated also. They could certainly be employed advantageously in aerosol flow problems, such as dynamic dilution. There is much room for aerosol electrification investigation and here, too, microorganisms could be used.

The Preparation and Biological Application of Airborne Simulants of Fallout from Nuclear Detonation*

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Among the many air pollution problems which confront us, one of the most recent and potentially the most hazardous is that presented by radioactive aerosols formed in nuclear detonation or in controlled nuclear fission. In order to assess the radiation hazard from the inhalation of fallout at early intervals following nuclear detonation, it is necessary to determine the deposition and retention of fallout in animals under controlled laboratory conditions. Partial information on the internal radiation hazard from fission products is available from previous studies of the metabolism of certain of the long-lived radionuclides individually inhaled or administered parenterally to animals[1,2]. Experiments involving the inhalation and metabolism of the whole spectrum of newly-formed fission products are necessarily limited by the difficulty of procurement of the radioactive material and its preparation as an aerosol for the exposure of animals.

Since the metabolism, and consequently the radiation hazard from inhaled fission products associated with fallout, depends to a great extent on the particle size and chemical properties of the carrier material used, it is necessary to study a variety of simulants. In the present experiment, 3 basic types of fallout simulants were developed. Simulant I consisted of fission product chlorides dissolved in sea water and generated as a liquid aerosol. Simulant II contained fission product chlorides dissolved in sea water to which dirt was added and generated as a liquid aerosol. Simulant III was composed of the fission product chlorides adsorbed completely on dirt particles, and generated as airborne particulates. A large number of mice were then exposed to these simulants in a specially designed apparatus.

Thus, the present study attempts to reproduce in the laboratory the acute exposure of mice to early fallout (2 to 3 days old) from various types of nuclear detonation. These experiments provide data necessary for an evaluation of the inhalation hazard. The method of aerosol preparation, and the physical and chemical characterization of the aerosols are described in the first portion of this paper. Data on uptake, distribution, and retention of one of these simulants in exposed animals are presented in the second portion.

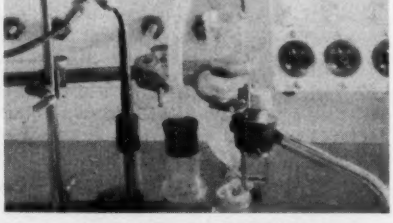

Fig. 1. Capsule breaker loaded with capsule containing uranium. Stang precipitator is behind the capsule breaker.

Preparation, Generation and Characterization of Fallout Simulants

Preparation of Simulants

All 3 forms of fallout simulant were prepared from neutron irradiated uranium obtained from the Materials Testing Reactor. The material was delivered to this laboratory, the simulants prepared and the animals exposed within 2-3 days after its removal from the reactor. To this mixture of fission products appropriate carrier material was added to form each of the 3 types of simulant previously described.

For the preparation of simulants I and II, fission product mixture in multicurie amounts was dissolved in HCl. This solution and total carrier (inactive isotopes of fission elements) were then added to sea water. To the second simulant mud was added in a quantity to produce a liquid-solid mass ratio of 100:1.

Simulant III (dry airborne particles) was prepared by adding the fission product chlorides to a solution of previously prepared dirt particles. These particles were Ambrose clay loam of less than 325 mesh size. The particles and fission product mixture were evaporated to dryness in a ball mill to insure mixing. The resultant simulant consisted of dirt particles with fission products adsorbed on the surface. The particles had a solubility of 8% in water and 18% in an HCl solution of PHl.

Since multicurie quantities of fission products were used in the preparation

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[1]R. Abrams, et al. Metabolism of Inhaled Fission Products Aerosols. U. S. Atomic Energy Commission, MDDC 248, 1946.

[2]J. G. Hamilton, The Metabolic Properties of Fission Products and Actinide Elements. *Rev. Mod. Physics*, **20**, 718, (1948).

* Presented at the American Chemical Society Symposium on Air Pollution at Atlantic City, N.J., Sept. 16-21, 1956.

Fig. 2. Arrangement of apparatus for exposing mice to radioactive fallout stimulants. The lead shielded gloved box at the right contains the aerosol generator. The gloved box in the center contains the animal exposure chambers.

of all simulants, remote handling was necessitated in all steps of the procedure. The fission products were shipped from Arco in a quartz capsule. This capsule was remotely loaded into a capsule breaker, and the whole assembly was placed in the upper chamber of a Stang precipitator, (Fig. 1). The precipitator was separated into an upper and lower chamber by a medium fritted glass disc. A spring loaded plunger was used as the capsule breaker, (Fig. 1). The precipitator was first flushed with nitrogen, after which the capsule was broken, allowing the fission products to fall onto the glass frit. The fission products were then dissolved in HCl, and the solution was drawn into the lower chamber of the precipitator and brought to pH6 with sodium hydroxide. The neutralized solution was then permitted to enter into the aspirator pot below which contained sea water or the mud slurry.

Simulant III was prepared by adding the fission product solution described above to a 1:1 solution of dirt particles. These clay loam particles and the fission products were placed in a ball mill where they were thoroughly mixed, evaporated to dryness and ground to insure a maximum size of 40μ.

Aerosol Generation

The experimental set-up for generating the aerosol and exposing the animals is shown in Fig. 2. The equipment consists of: (1) an aerosol generator, (2) the animal exposure chambers, (3) sample collectors for measuring particle size and aerosol concentration, and (4) supporting equipment, (pumps, *etc.*).

The aerosol generator for the slurry simulant II (Fig. 3) is located in a gloved box shielded with 2 in. of lead as illustrated in the preceding figure. The fog-generating pot used with Simulants I and II is a three-necked flat bottom flask with a capacity of I *l*. The air driven aspirator in one side arm of the flask has a horizontal air hole (0.0135) in. diam.) and a solution hole

Fig. 3. Simulant II, aerosol generator.

(0.0280 in. diam.) oriented at 60° to the air hole. The liquid or slurry is drawn up through the large hole by the low pressure area created by the high velocity air stream, and is sheared off into fine droplets. The Stang precipitator was located in the other side arm of flask. A stopcock was located between the lower chamber of the precipitator and the pot. Side arms were provided for applying either pressure or vacuum to either or both chambers of the precipitator.

The aerosol is carried from the central neck of the generating chamber to the distribution manifold at the entrance of the animal exposure chamber by half-inch tygon tubing. This manifold (seen on top of the animal exposure chamber, Fig. 4) consists of a series of venturi tubes 11 mm. in diam. with 1 to 2 mm. tubes inserted coaxially. The tubes act as jet pumps, with the central tube delivering humidified air as the pumping fluid. The 2 air streams mix to form an aerosol of

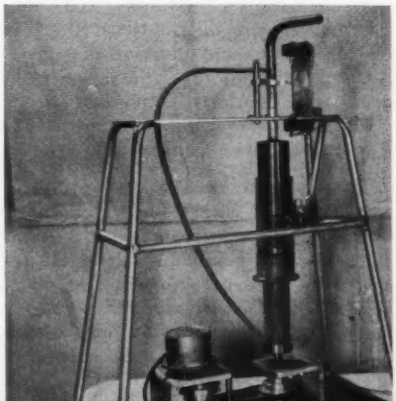

Fig. 5. Simulant III (dry particle) aerosol generator.

Fig. 4. Mouse inhalation chambers. Method of simultaneously exposing mice to 3 different concentratins of radioactive aerosol is illustrated.

lower concentration, thus permitting the concentration to be varied.

The aerosol generator used with simulant I was identical except that the three-necked flask was replaced with a 6 in. diam. glass cylinder 15 in. in length.

Simulant III was placed in a specially designed areosol generator, (Fig. 5). The generator was designed to provide a stream of airborne particles at a constant concentration level. The rotation of the outer tube provides a constant advance of a brush against the surface formed by the particles. The particles thus agitated are picked up by the airstream and delivered to the exposure chamber.

Animal Exposure Chambers

Three animal exposure chambers were situated in the air tight gloved box, (Fig. 4). A large chamber (Chamber I) was designed to hold 64 mice in 8 rows as shown in the figure. Two smaller chambers (Chamber II and III) held 18 mice each. The exposure chambers were made of 6 in. diam. lucite tubing containing 1½ in. holes symmetrically arranged. Tapered 50 ml. centrifuge tubes containing the mice were mounted in bored rubber stoppers and placed in these holes. The tips of these centrifuge tubes were cut off so as to permit only the noses of the mice to protrude into the airstream. The mice were held in this position by a cotton wad backed up by a rubber stopper. This method of exposing the mice was designed to minimize both ingestion of the fallout material and deposition on the fur.

Aerosol Assay Equipment

The apparatus for aerosol assay consisted of two 5 cm. millipore filter paper samples. These were used to determine

the air activity in animal exposure Chambers I and II. Part of the aerosol was drawn successively through the millipore filter where the particulates were removed for counting, then through a tapered base flow meter to determine the flow, and finally through a Chemical Corps M-11 cannister, which served as a safety filter. A sampler consisting of a 40 ml. centrifuge tube layered with cotton, activated carbon, drierite, and cotton was used to determine the concentration of airborne activity in any chamber. This sampler was connected to the system in the same manner as the millipore filter.

The static head on each flowmeter was read on oil filled manometers (sp. gr. 0.834). Draft gages were used to measure the pressure differential between the gloved box, containing the exposure chambers, and atmospheric, and also between the lead shielded box and atmospheric. Oil manometers were used to determine the static pressure in Chamber I, and the nitrogen pressure and/or vacuum on the chambers of the Stang precipitator. Manifold valves controlled the vacuum to all samplers and nitrogen and vacuum in the precipitator.

Auxiliary Equipment

The auxiliary equipment consisted of 2 compressed air bottles, manifolds, pressure regulators, and flow meters to gage and control the air pressure and flow to the aspirator and jet pumps. Gas washing bottles were used to humidify the air delivered to each of the jet pumps. Two vacuum cleaners were connected through M-11 cannisters, one to the exposure chamber exhaust manifold and the other to the gloved box, to maintain negative pressure heads. A separate 100 cfm. blower and filter exhausted the lead shielded gloved box. A magnetic stirrer under the aerosol generator stirred the slurry continuously. Drain taps were located at low points on the line transporting the aerosol from the aspirator to the distribution manifold to prevent water locks.

The aerosols, after passing through the 3 animal chambers, were drawn through a filter designed to remove all radioactive particulates before being discharged into the laboratory hood. The absolute pressure in the system was maintained at 0.7 in. water below atmospheric, while the gloved box containing the animal exposure chambers was maintained at 0.2 in. water below atmospheric by a pump and filter system.

These negative pressures were maintained to prevent radioactivity from escaping into the room during the operation of the equipment.

Aerosol Size

The 2 methods used for determinating particle size did not prove entirely satisfactory in this experiment. The 2 techniques were, first, microscopic examination of an exposed water sensitive film[3,4], and secondly, a sub-microscopic method using an electron microscope. In the first method, a water sensitive film was placed at the center of each chamber, perpendicular to the aerosol flow. The craters produced by the droplets became visible when the exposed film was developed under ultra-violet light. Photomicrographs were made of several areas of the film, and the number and size of the spots counted. In the second method the spots produced on formvar slides were measured under an electron microscope. The droplets drying on the slides left a residue (predominantly of sodium chloride) which produced an image on the electron microscope screen. These images were round and mainly of uniform density. The cubic structure of NaCl crystals was often visible.

The maximum droplet diam., with simulant I as observed in Chamber I was 3.7 and the minimum diam. was 1.3μ. The size distribution had a mean of 1.8 and a standard deviation of 0.43μ. The spots observed with the electron microscope varied from 0.05-0.6μ in diam. with a mean of 0.28μ. The mean droplet size for simulant II was considerably larger than that observed with simulant I.

The formvar surface of the electron microscope slides had wetting characteristics different from those of the water sensitive film, thus it remains to correlate the microscopic and submicroscopic size distributions. Work is now in progress to improve the physical characterization of the experiment aerosols particularly as regards size.

Aerosol Airborne Concentration

The air flow rates to the manifold were adjusted to provide a concentration ratio of airborne activity of 100 : 10 : 1 in Chambers I, II, and III respectively. The jet aspirator was operated at 120 psig, giving a flow rate of 22 ft.^{3}/hr. for simulant I and at 100 psig giving a 20 ft.^{3}/flow rate for simulants II and III.

The relative concentrations of airborne activity was simulant I (obtained by means of tube samplers) were 100 : 12.4 : 4.4 for Chambers I, II, and III respectively. The deviation from the calibrated ratio may have arisen from errors in calibration caused by the different flow rates in the manifold. It is also possible that the airborne activity did not exactly follow the division of air flow.

With simulant II the samplers indicated airborne activity ratios of 100 : 29.3 : 3.6 in Chambers I, II, and III respectively. The difference in concentration ratios here as compared to those in the simulant I experiment were due to the replacement of the original manifold.

Biological Application of Simulants

Radioactive fallout enters the body through inhalation and ingestion and concentrates in various tissues, where it acts as a source of internal radiation. The amount of fallout material absorbed through the lung and the intestine is determined by its solubility, chemical properties and physical state. Thus it happens that only a few fission products enter the blood stream and become available to the tissues. However, the amount required to produce injurious effects to the body are minute. Most of the fission products with long radioactive lives are concentrated by the skeleton where they are *fixed* for long periods of time. The radiation damage to the body from internally deposited fission products is therefore primarily to the adjacent, highly radiosensitive bone marrow.

An estimate of the internal radiation hazard following an inhalation exposure requires the determination of the initial whole body uptake and the fractional uptake and retention by the various tissues. If, in addition, the average energy and the radioactive decay rate of the fission products in the fallout taken up are known, the dose to the tissues can be calculated. Comparison of these values with established values for permissible concentrations then can provide a measure of the internal radiation hazard.

Consideration of the many factors determining the degree of internal exposure indicates that the characterization of the hazard by physical instrumentation alone is exceedingly difficult. There are presently available only few biological data on the uptake and metabolism of the early radioactive fallout

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(3) N. H. Farlow. A Physio-Chemical System for Water Aerosol Measurement. USNRDL-TR-49.

(4) N. H. Farlow and F. A. French. Calibration of Liquid Aerosol Collectors by Droplets Containing Uniform Size Particles. USNRDL-TR-50.

in terms of the factors listed. Thus, exposure of small animals to the whole spectrum of early fallout material is an empirical method leading to a rapid and convenient evaluation of the internal hazard associated with fallout, and bypassing the detailed and laborious physical characterization of the airborne fallout which is otherwise required.

In the present study a number of mice were exposed to fallout simulant II. The radioactivity of the fission products in the fallout simulant makes possible the tracing of the metabolic fate of the inhaled material. The amount of fallout material entering the respiratory trace and deposited in the tissues of exposed animals was determined by direct measurement of tissues taken from animals sacrificed immediately after exposure. In addition, by serial sacrifice, the amount of material maintained in the lung and other tissues at various times after exposure was also determined.

Experimental

Animal Exposure: Forty mice were exposed for 3 hrs. in Chamber I, and then removed and placed in metabolism cages for collection of excreta. The mice were sacrificed in groups of 6 at 1 hr., 3 hrs., and 1, 3, 7, 14 and 30 days following exposure.

In the second experiment, 2 groups of 15 mice each were exposed for 1 hr. and 3 hrs., 5 in each of the 3 chambers simultaneously for the 2 exposure times. The whole body activity of these mice was then measured. In addition, 1 mouse from each group was sacrificed, and the skin and internal organs were removed and their gamma activities determined.

Tissue Assay for Radioactivity: Previous experiments have shown that gamma activity measurements satisfactorily reflect the total fission product activity. The distribution of gamma activity in the first experiment was determined in the following organs and tissues: respiratory tract (from upper end of larynx) and lungs, liver, skeleton*, thyroid, head and gastro-intestinal tract (from top of oesophagus to the anal region). The tissues analyses were performed by determining the gamma activity with a sodium iodide gamma scintillation counter.

For the determination of whole body gamma activity, the mice were anaesthetized and placed in a test tube which was then lowered into a 4 in. gamma ionization chamber. This instrument was calibrated against both RA^{226} and Co^{60} standards.

Film badges were placed around each animal exposure tube to record external gamma and beta activity to which the mice were exposed.

Results and Discussion

Uptake and Retention by Animal Tissues: The distribution of the radioactive fallout simulant to the tissues and organs of mice exposed to the above simulant for 3 hrs. and serially sacrificed at times from 1 hr. to 28 days is shown in Fig. 6. Immediately following exposure, most of the fission products (as reflected by their gamma activity) were found in the G.I. tract, the lung and respiratory tract, the skeleton and the head. Approximately 80% of the internal activity was found in the G.I. tract at 1 hr. after exposure. All the activity entered the body by inhalation. The smaller particles penetrated to the alveolar tissue, but much of the radioactive material was apparently associated with larger particles which were moved back up the respiratory tract and subsequently swallowed. Only a small fraction of the material in the G.I. tract was absorbed into the body, the bulk being excreted. At 1 hr. post exposure, the head and respiratory system each contained 10% of the gamma activity found in the G.I. tract at 1 hr. post exposure. At this same time the activity in the skeleton and liver was approximately 2% of the activity in the G.I. tract and the activity in the thyroid was 0.3% of the activity in the G.I. tract. The tissue dose (d./m./gm.) was highest for the lung and thyroid at this time.

An approximation of the internal radiation dose rate to individual tissues can be calculated by applying the following equation:

$$I_t = k \frac{Q}{w} \bar{E}_\beta$$

where:

I_t = dose rate in rad./hr.

Q = beta activity in d/gm. tissue (gamma activity measured experimentally is converted to beta activity using the ratio of gamma photons to beta particles is a fission product mixture at this time)

W = weight of tissue in gm.

$\bar{E}_\beta$ = average energy of beta particles

An application of this calculation and a discussion of the assumptions implicit in this approximation are

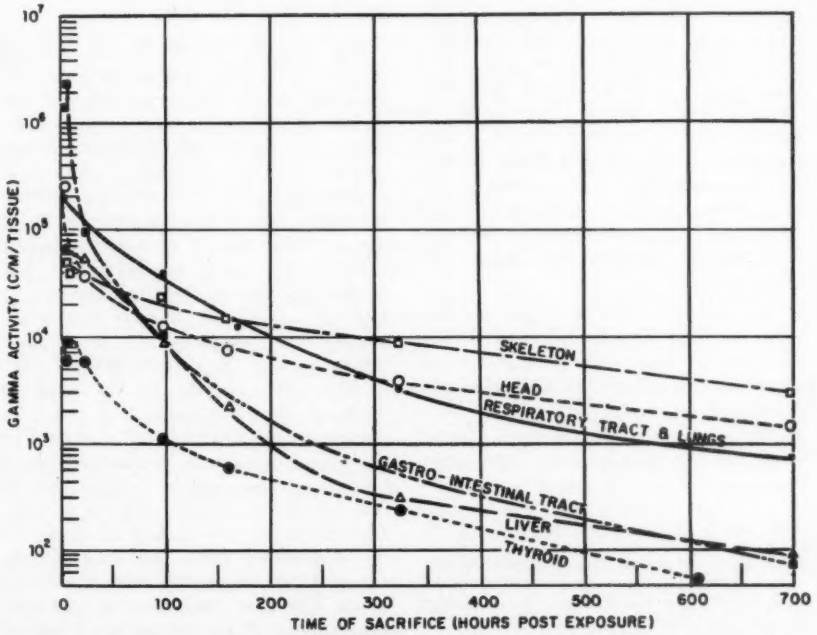

Fig. 6. Uptake and distribution of gamma activity in tissue of mice exposed to fallout Simulant II.

* The ratio of total skeletal mixed fission product content to the concent of one tibia was found to be 27. From this ratio, an estimate of the total skeletal activity was calculated.

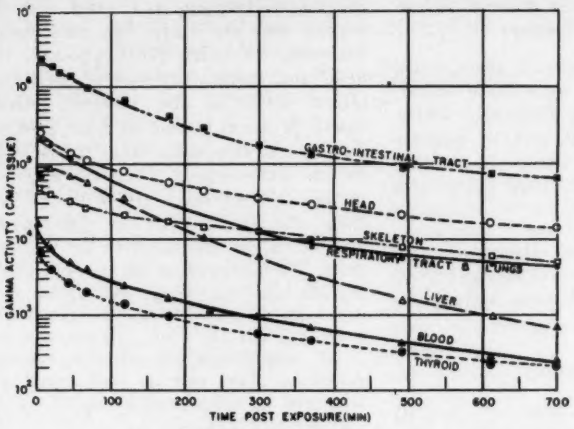

Fig. 7. Radioactive decay of fallout Simulant II in the animal tissues.

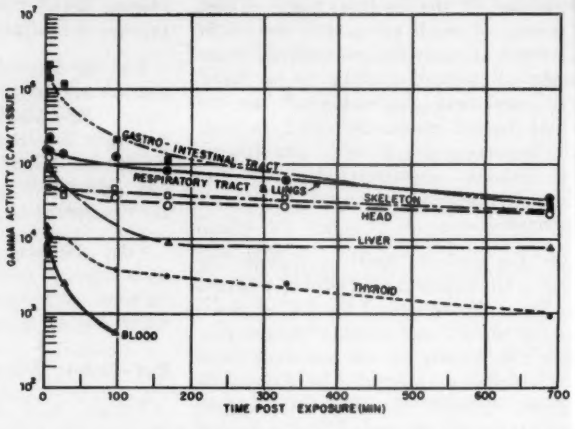

Fig. 8. Biological decay of fallout Simulant II in animal tissues.

presented in another report[5].

The activity in all of the tissues fell off rapidly as a function of time, decreasing to a few per cent of the original activity by the 28th day. This drop in activity in a function of 2 simultaneous processes: the radioactive decay of the fission products and the biological loss (turnover) of the simulant material itself from the tissues.

Radioactive Decay of Tissue Activity: The gamma activity of the tissues of animals sacrificed at 1 hr. post exposure was measured at intervals over a 30 day period. The curves of the radioactive decay of gamma activity of the fission products deposited in various tissues are shown in Fig. 7. The radioactive decay curves reflect the composition of the fission product mixture taken up by each tissue. The similarity of the isotopic distribution in most of the tissues can be seen from their very similar decay curves. The decay of gamma activity in the skeleton is considerably slower than the decay in other tissues, indicating a fractionation of the fission product mixture by the skeleton. Bone concentrates more long-lived fission products than any of the other tissues.

The activity in the lung and respiratory tract and the G.I. tract decays for the first 4 days with a half life of about 50 hrs. This indicates the predominance of either one isotope or a group of isotopes with a fixed composition during this period. The curves of decay of activity in the other tissues lie between that of the tibia (with the slowest decay rate) and that of the liver (wtih the fastest decay rate).

Biological Decay of Simulant Material: The gamma activity of each tissue taken from mice sacrificed at various time intervals following exposure was calculated back to 1 hr. post exposure. The corrections for radioactive decay were made by use of the above-mentioned radioactive decay curves. If the value of gamma activity in each tissue at the various sacrifice intervals following exposure is corrected for radioactive decay, the resultant curve approximately describes the biological decay of the fallout simulant in that tissue. The curves of biological decay are shown in Fig. 8.

The activity of the blood fell off more rapidly than that of the other tissues, due to the rapid exchange of material from blood to other tissues. After 4 days the activity of the blood was not detectable. The biological decay of radioactive material in the gastro-intestinal tract was also very rapid, as the material was very rapidly passed through the tract and excreted. The gamma activity of the liver fell with a half-life of 35 hrs. for the first week. During the remainder of the experimental period the activity fell off very slowly. The activity in the skeleton built up to a maximum at 3 hrs. post exposure and then fell off slowly. The biological decay may be described by a very low rate constant, comparable to that of the liver after the first week. The curve of the biological decay of the respiratory tract and lung activity can also be separated into 2 components. The first component is probably associated with the initial rapid loss of activity which was carried up the respiratory tract and then swallowed. The second component, with a half-life of 25 days, may be associated with the slower release of the particulate matter retained by the alveolar tissue.

Whole Body Uptake of Activity: The whole body activity following the 3 hr. exposure was proportional to the airborne activity in each chamber. Whole body concentration ratios of 100: 32: 4.7 were found, compared to the airborne activity ratios of 100: 29.3: 3.6 in chambers I, II and III respectively. The whole body activity was not proportional to the length of exposure time. The animals exposed for 3 hrs. had approximately twice the activity of the animals exposed for 1 hr. About ⅔ of the whole body activity was found on the skin and about 20% in the gastro-intestinal tract of the exposed mice.

The gamma dose to which the mice in chamber I were exposed, as determined by film badges was 25-35 mr./hr.

Summary and Conclusions

Production of radioactive aerosols by nuclear detonation or controlled nuclear fission is the most recent air pollution problem to confront us. As yet. the nature and degree of the inhalation hazard associated with these radioactive aerosols has not been clearly delineated. Characterization of airborne radioactive fallout by physical measurements alone does not allow a meaningful evaluation of the human hazard to be made, inasmuch as the necessary biological data required for interpretation are not available.

The present study describes the development of an experimental method for assaying the inhalation hazard, using mice as biological indicators. The technique used required: (1) the development and characterization of

[5] S. H. Cohn, et al. Radiotoxicity Resulting from Exposure to a Fallout Simulant. II. The Metabolism of an Inhaled and Ingested Simulant of Fallout Produced by a Land-Based Nuclear Detonation. U. S. Naval Radiological Defense Laboratory, TR-118 (Jan. 11, 1957).

simulants of airborne fallout; (2) the design of equipment for generating the simulant and exposing small animals under controlled laboratory conditions; (3) determination of the uptake and retention by various tissues of the radioactive materials; (4) evaluation of the hazard to the animals by this exposure in terms of dose.

The procedures used in this experiment are unique in several respects, insofar as studying an inhalation problem is concerned. Only a short time was available for procuring the radioactive material, preparing the simulant and exposing the animals. Further, remote handling of multicuric levels of radioactive materials used was necessary. It was necessary to design the animal exposure chambers to provide only an inhalation exposure.

Three general types of fallout simulants were developed, one of which was applied in the biological experiment described. Further studies are now being carried out with the other fallout simulants.

The Concurrent Determination of Sulfur Dioxide and Nitrogen Dioxide in the Atmosphere*

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The fact is widely recognized that conductimetric methods for the estimation of sulfur dioxide concentrations in the urban atmosphere are not entirely specific. Alternative methods of varying degrees of specificity are available, but the literature is lacking in quantitative comparisons of the conductimetric methods and other methods considered to be more specific.

Another consideration which justifies the investigation of alternative methods is that automatic recording instruments based on the continuous measurement of variations in the conductivity of dilute sulphuric acid solutions are so designed that differences in concentration of 0.01 ppm. are not too precisely measurable. The sensitivity of recording conductimetric instruments can, of course, be increased greatly, but it is worth considering whether, in circumstances when daily averages do not rise much above 0.03 ppm. and the duration of periods when the concentration rises above 0.20 ppm. is less than 5% of the total time, alternative methods might be more useful. It is worth mentioning, also, that the servicing of autometers set to register substantial pollution levels is exacting, and the task of reading the charts is very far from simple. Presumably, autometers set to a higher sensitivity would require even more careful servicing, and reading the charts would be correspondingly more difficult.

In the work described at a sampling station in Windsor, Ontario, it is shown that conductimetric determinations yield consistently higher values than a colorimetric method based on the chromogenic reaction of fuchsin, formaldehyde, and sulfite. Differences are of the order of about 5 to 10 pphm., at the pollution levels encountered during this work, 0 to 30 pphm., and may be accounted for in part by the effect of nitrogen dioxide on the fuchsin-formaldehyde-sulfite colour. In the discussion later an attempt is made to assess the usefulness and validity of both methods for sulfur dioxide, and the significance of concurrent estimations of nitrogen dioxide concentrations.

Experimental

Samples for comparison of conductimetric and colorimetric determinations of sulfur dioxide, and for the determination of concurrent nitrogen dioxide concentrations were aspirated with air by means of 3 suitably adapted *Aseco Automatic Impingers*[9] operated simultaneously. For sulfur dioxide, the solution was aspirated at rates of 15 *l.*/min. for 30 min. of each hr., through 50 ml. of absorbent in each of the *impinger* tubes in two of the machines. For nitrogen dioxide, air was aspirated at 2 *l.*/min. through 30 ml. of absorbent in a specially constructed absorption tube fitted with a medium porosity fritted disk. Rates of aspiration were measured by rotameters of suitable range built into the assembly.

The sampling point common to all 3 machines was a point on the side of a 4 story building about 15 ft. above the sidewalk of a street paralleling the south bank of the Detroit River 100 yd. away.

Following 24 hr. runs of the automatic samplers, the aspirated samples were analyzed by the methods indicated.

Colorimetric Method for Sulfur Dioxide

The chromogenic reaction of sulfite with basic fuchsin-formaldehyde reagent, developed by Steigman[1], as adapted to the estimation of sulfur in histological samples by Grant[2] has been dealt with in detail in a number of papers on the determination of atmospheric sulfur dioxide.[3,4]

The method is said to be relatively specific for sulfur dioxide, sensitive, and fairly simple. The method as described by Paulus, Floyd and Byers[4] was used with a few modifications.

Since each new batch of colour reagent required standardization, decol-

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-4, 1956.

(1) A. Steigmann. A New Color Reaction For Sulfurous Acid, The Thiol Group and Formaldehyde. *J. Soc. Chem. Ind.*, **61**, 18-19 (1942).

(2) W. M. Grant. Colorimetric Determination of Sulfur Dioxide. *Anal. Chem.*, **19**, 345-6 (May 1947).

(3) P. F. Urone and W. E. Boggs. Acid-Bleached Fuchsin in Determination of Sulfur Dioxide in the Atmosphere. *Anal. Chem.*, **23**, 1517-19 (Oct. 1951).

(4) H. J. Paulus, E. P. Floyd and D. H. Byers. Determination of Sulfur Dioxide in Atmospheric Samples. *Amer. Ind. Hygiene Assoc. Quart.*, **15**, 4 (Dec. 1954).

(9) W. L. Wilson. An Automatic Impinger for Air Sampling. *J. Air Poll. Control Assoc.*, **4**, 8-13 (1954).

ourizing with activated carbon was omitted. Any batch of reagent whose calibration constant differed substantially from that of previous batches was discarded.

Optical absorbences were read on a Coleman Model 14 Spectrophotometer, using Class B cuvettes. N/10 sodium hydroxide containing 5% glycerin was used as a collecting medium.

Paulus *et. al.*[4] point out that the smallest amount of sulfur dioxide accurately measurable by the colorimetric method is about 0.1 μg./ml. of sample, and Urone and Boggs[3] remark that the standardization curve is linear between the concentrations limits of 0.1 and 11.0μg. of sulfur dioxide/ml. of the solution measured colorimetrically. These observations are confirmed in the present work by the failure of numerous calibration curves to extrapolate exactly to zero. The reaction mixture in which colour development is measured behaves as though sulfur dioxide below a certain low threshold concentration does not react with fuchsin-formaldehyde. In the present work, the diffculty was overcome by adding to the fuchsin-formaldehyde reagent, just before use, about 0.2μg./ml. of sulfur dioxide in the form of sodium metabisulfite. In the determination of the standardization constant (Fig. 1) therefore, and in the routine analysis of unknowns, the reference standard is a solution already showing a little colour.

A consequence of the described addition of sulfur dioxide to the colour reagent was that, not infrequently, computation yielded formally negative values for sulfur dioxide concentrations in air. A possible explanation is that during aspiration, together with sulfur dioxide which produces colour when the fuchsin reagent is added, something else is collected which reduces the fuchsin-sulfite colour. Concurrent determinations of nitrogen dioxide by the Saltzman[5] method gave values for nitrogen dioxide in air of a magnitude intermediate between that of the fuchsin and conductimetric sulfur dioxide concentrations, and experimental addition of known increments of sodium nitrite to fuchsin-formaldehyde-sulfite reaction mixtures showed an approximately quantitative reduction of colour (Fig. 2).

[5] B. E. Saltzan, Colorimetric Microdetermination of Nitrogen Dioxide in the Atmosphere. *Anal. Chem.* **26**, 1949-1955 (1954).

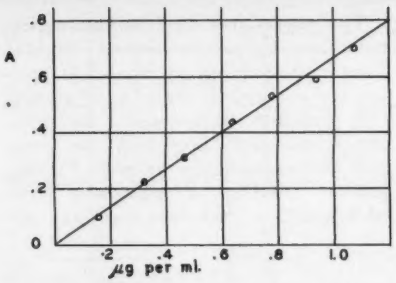


Fig. 1. Standardization curve for fuchsin reagent colorimetric constant for sulfur dioxide determinations.

The inference is obvious that nitrogen dioxide interferes with the fuchsin determination of sulfur dioxide. Where sulfur dioxide levels are substantial, say of the order of 50 pphm. or higher, the interference is probably less significant. If, however, sulfur dioxide levels are of about the same order as nitrogen dioxide levels, fuchsin values could be misleadingly low.

The following is a sample calculation of sulfur dioxide concentration, as determined by the fuchsin method and use of the calibration curve shown in Fig. 1:

$$\text{pphm.} = \frac{10^5}{V} \times v \times 1.8 \times dA \times$$

$$\frac{40}{20} \times \frac{1}{64 \times 10^6} \times 22.4 \times 10^3 \times \frac{298}{273}$$

where V = volume in ml. of air aspirated

V = volume in ml. of absorbent

1.8 is the slope of the standardization curve in micrograms of sulfur dioxide/ml. of the reaction mixture made by adding 20 ml. of absorbent to 20 ml. of dye reagent.

dA = the difference in absorbence of reaction mixtures containing respectively 20 ml. of absorbent with collected sulfur dioxide and 20 ml. of unexposed absorbent.

The significance of the other constants is obvious.

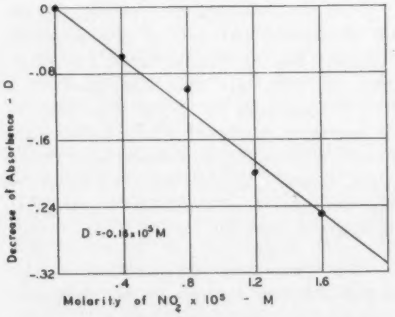


Fig. 2. Decrease in absorbence of sulfur dioxide-fuchsin reaction mixture vs. molarity of added nitrogen dioxide.

For $V = 450{,}000$ aspirated through 50 ml. of absorbent at 25°C. and 760 mm. and $dA = 0.39$, pphm. = 5.9

Conductimetric Method for Sulfur Dioxide

Collecting medium — 6×10^{-5} N sulfuric acid, containing 1 ml./*l.* of 20% hydrogen peroxide.

Equipment—

A calibration constant was determined by plotting measured conductivities of sulfuric acid solutions against normalities calculated from dilution ratios. For the cell used, the normality was 2.70 times the conductivity.

Computation of sulfur dioxide concentrations from measured conductivities is easy and needs little elaboration. For example, for 450 *l.* of air at 25° C. and 760 mm. aspirated through 50 ml. of absorbent, the conductivity of the absorbent increased from 2.8×10^{-5} mhos. to 4.4×10^{-5} mhos. and the concentration is computed as follows:

$$\text{pphm.} = \frac{10^5}{1} \times \frac{1}{4.5 \times 10^5} \times \frac{50}{10^3} \times \frac{298}{273}$$

$$\times 11.2 \times 10^3 \times 2.7 \times 1.6 \times 10^{-5} = 5.9$$

In the above, the assumption is made that 50 ml. of absorbent delivered to the *impinger* remains unchanged in volume at the end of aspiration. This is not strictly accurate; measurement of the total volume of absorbent delivered to the impinger during a day's run and measurement of the total volume delivered from the impinger showed a difference of 8%. If the difference were entirely due to evaporation of water, the calculated sulfur dioxide concentrations would be high by 8%. Spray carry over, which would result merely in a reduction of volume without change in normality, undoubtedly accounts for part of the 8% loss, however, and the result of such a volume reduction would be a diminution of the calculated sulfur dioxide concentration. Without accurate measurement of the separate effects of evaporation and spray losses, which are opposite in sign, no corrections for the 8% loss have been applied to the conductimetric values for sulfur dioxide.

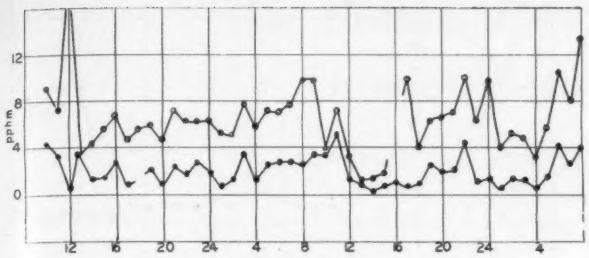


Fig. 3. (Above) Sulfur dioxide by concurrent conductimetric —o— and colorimetric ——— methods, Aug. 15, 16, 17, 1955.

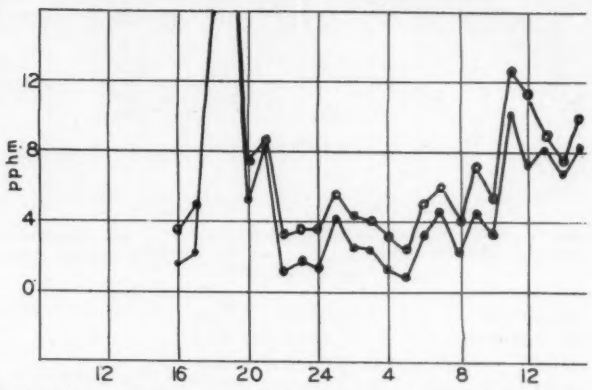


Fig. 4. (Right) Sulfur dioxide by conductimetric —o— and colorimetric ——— methods, Aug. 22, 23, 1955.

Colorimetric Method for Nitrogen Dioxide

Air was sampled for nitrogen dioxide determinations concurrently with the sampling for sulfur dioxide determinations. Analyses for nitrogen dioxide were made by the Saltzman[5] method, using a Coleman Model 14 Spectrophotometer. The absorbing reagent is a mixture of sulfanilic acid, N-(1-naphthyl)-ethylene diamine dihydrochloride and acetic acid.

To suit operating conditions of the automatic samplers, a fritted glass disk, medium porosity, was sealed into an absorption tube requiring about 30 ml. of absorbent to immerse the disk adequately. About the lowest practical rate of aspiration which would yield readable colour and still remain in balance with rates necessary for sulfur dioxide was 2 *l.*/min. This rate may be undesirably high for efficient absorption, but spot checks on single aspirations, made by setting a second fritted glass bubbler in series with the permanently installed absorption tube, indicated that absorption was about 80% complete.

Systematic sampling of air for nitrogen dioxide by the above method has not, as yet, been carried on for a sufficient length of time to deal thoroughly with a number of questions relating to the pick up of color by absorbent standing exposed to the laboratory atmosphere before and following aspiration of air, and other possible variables. The results thus far indicate the desirability of careful, extended investigation of nitrogen dioxide as a significant factor in pollution of the Windsor atmosphere and in other areas.

Discussion of Analytical Results

Values for concurrent conductimetric and colorimetric determinations of sulfur dioxide and for simultaneous colorimetric measurements of nitrogen dioxide are shown conveniently in a series of graphs.

Fig. 3, 4, 5 and 6 show the comparative values of conductimetric and colorimetric determinations for sulfur dioxide, subject to the qualification that conductimetric values are somewhat too high by the effect of evaporation of water from the absorbent, and colorimetric values are too low by the bleaching effect of nitrogen dioxide on the fuchsin-formaldehyde-sulfite colour.

For routine monitoring of sulfur dioxide concentrations where values are appreciable, the conductimetric bridge method with collection of air samples by the automatic impinger is less time-consuming than the colorimetric method with similar equipment. Automatic sampling and routine collection of samples followed by either method of analysis is suggested as possibly a cheaper and more convenient routine than the continuous operation of instantaneous Thomas autometers[8] for urban atmospheres. Where 6 hr. averages are sufficient for statistical purposes, the automatic impinger method, requiring the analysis of only four composite samples a day for each machine, would almost certainly be less exacting than the very considerable task of reading the autometer charts for equivalent periods, unless short-period peak concentrations are required for assessing effects on vegetation and other purposes.

Fig. 7 and 8, indicating concurrent values for nitrogen dioxide and sulfur dioxide, are significant in showing that nitrogen dioxide is present in the atmosphere in concentrations of the same order of magnitude as low levels of sulfur dioxide pollution.

Corrections for the effect of nitrogen dioxide on the colorimetric sulfur dioxide values are indicated in additional curves plotted in Fig. 9 and 10. The corrected fuchsin values are submitted as evidence that the difference between

[8] M. D. Thomas, J. O. Ivie, and T. C. Fitt, *Ind. Eng. Chem.*, Anal. Edl, 18, 383-7 (1946).

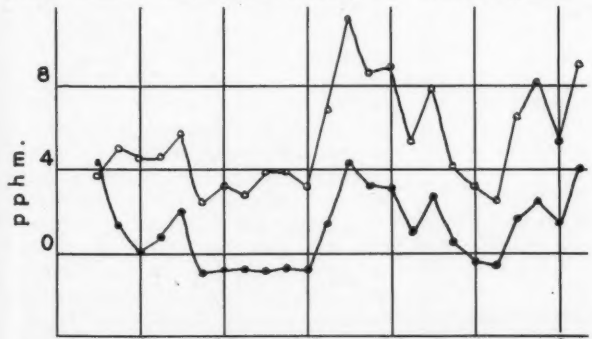
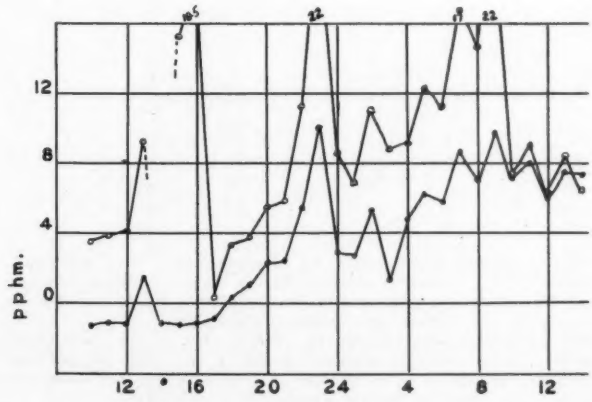


Fig. 5. (Above). Sulfur dioxide by conductimetric —o— and colorimetric ——— methods, Aug. 30, 31, 1955.

Fig. 6. (Right). Sulfur dioxide by conductimetric —o— and colorimetric ——— methods, Sept. 1, 2, 1955.



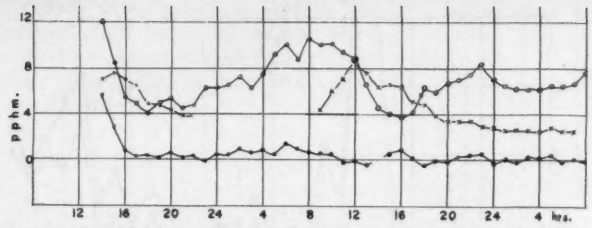


Fig. 7. Sulfur dioxide by conductimetric —o— and colorimetric methods; nitrogen dioxide —x— by the Saltzman method. Sept. 26, 27, 28, 1955.

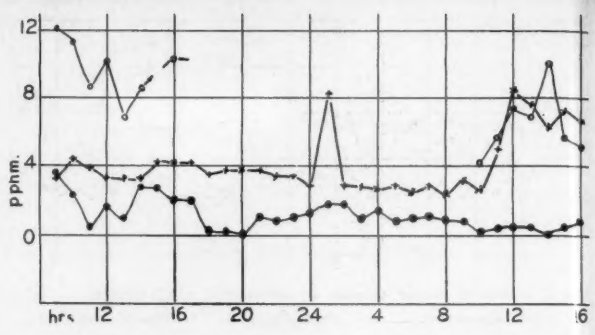


Fig. 8. Sulfur dioxide by conductimetric —o— and colorimetric ——— methods; nitrogen dioxide —x— by the Saltzman method, Sept. 28, 29, 1955

conductimetric and colorimetric values for sulfur dioxide can be accounted for, in part at least, by the presence of oxides of nitrogen.

The graphs illustrate the hourly variation in levels of sulfur dioxide and nitrogen dioxide from industrial and public activities of the Detroit River area, as influenced by meteorological factors. Nitrogen dioxide levels show approximately a similar trend to that of sulfur dioxide.

Cholak, Schafer and Yeager[6] have reported on nitrogen dioxide levels in a recent survey of the atmosphere of Washington, D. C. During a warm period the mean concentration was about 9 pphm. in contrast to a mean of 4 pphm. for a cold weather period. The highest concentration found was 39 pphm. Comparable mean levels exist in the Windsor area.

A recent areometric survey of the Los Angeles area[7] indicated an average diurnal variation of oxides of nitrogen in the autumn months of 1954 from values below 10 pphm. to peaks of over 25 pphm. for a number of sampling stations. The average diurnal peaks at one station rose to about 50 pphm. These levels are higher than those reported here for the Windsor station.

There is no doubt that nitrogen dioxide is a component of polluted urban atmospheres, and on occasion, almost comparable in importance to sulfur dioxide. Oxides of nitrogen are formed in all combustion processes from the oxidation of organic nitrogen compounds in the fuel and from the direct combination of nitrogen and oxygen at elevated temperatures in the air supplied for combustion. Recent investigations in the Los Angeles area have stressed the importance of the role of oxides of nitrogen in the photochemical oxidation of hydrocarbons and production of ozone, in the atmosphere, as a contributing factor to smog formation.

Summary

Concurrent determinations have been made of low concentrations of sulfur dioxide by the conductimetric and fuchsin methods; and of nitrogen dioxide by the Saltzman method, by means of 3 suitably adapted Automatic Impingers at a common atmospheric sampling point in Windsor, Ontario. Conductimetric determinations yielded consistently higher values for sulfur dioxide than the colorimetric method based on the chromogenic reaction of fuchsin, formaldehyde and sulfite. These differences may be accounted for, in part, by the presence of nitrogen dioxide in the atmosphere which reacts with the fuchsin reagent to lower the colorimetric sulfur dioxide value.

The nitrogen dioxide concentration levels of the atmosphere fluctuate in a manner similar to those of sulfur dioxide and are somewhat lower in magnitude than the conductimetric sulfur dioxide levels. When the fuchsin values are corrected for the effect of nitrogen dioxide, the colorimetric sulfur dioxide levels are in fairly close agreement with those estimated by the conductimetric method.

Data are present to show the hourly variation in sulfur dioxide and nitrogen dioxide in the Windsor atmosphere. The nitrogen dioxide levels reported thus far are lower than those found in the Los Angeles atmosphere.

[6] J. Cholak, L. J. Schafer, and D. W. Yeager, The Concentration of Ozone in the Atmosphere of Certain American Cities. *J. Air Poll. Control Assoc,* 5, 227-232 (1956).

[7] Air Pollution Foundation, Rept. No. 9, An Aeromatic Survey of the Los Angeles Basin, (August-November, 1954) Chapter VII.

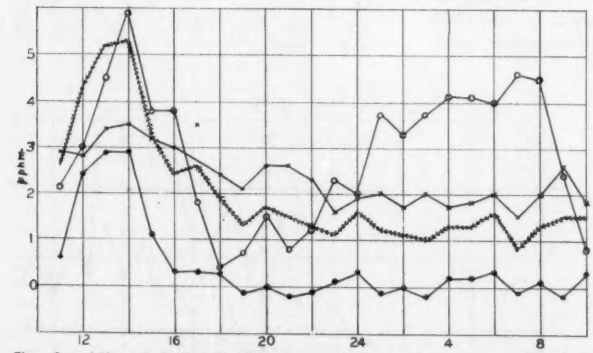


Fig. 9. (Above) Sulfur dioxide by conductimetric —o— and colorimetric ——— methods, nitrogen dioxide —x— by the Saltzman method; colorimetric sulfur dioxide ---- corrected by the calculated effect of nitrogen dioxide, Oct. 6, 7, 1955.

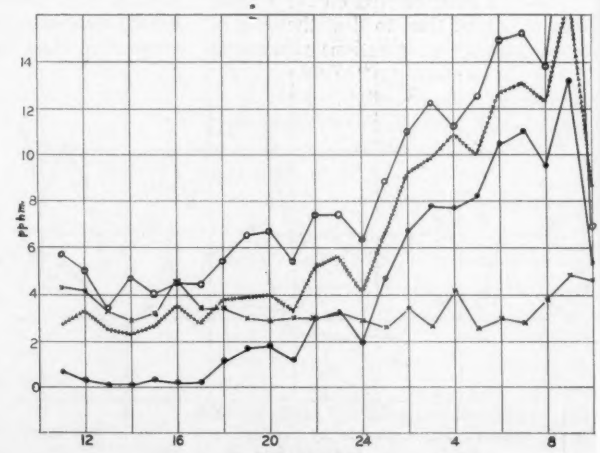


Fig. 10. (Right) Sulfur dioxide by conductimetric —o— and colorimetric ——— methods, nitrogen dioxide —x— by the Saltzman method; colorimetric sulfur dioxide ---- corrected by the calculated effect of nitrogen dioxide, Oct. 13, 14, 1955.

Air Pollution Control by a Sulfur Dioxide Scrubbing System*

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Little Rock, Ark.

Development groups in Olin Mathieson had been studying the problem of sulfur recovery for many years, in connection with work done with both sulfur recovery from sour gas and the recovery of sulfur dioxide from the tail gas of sulfuric acid plants. Up to that time, the economics of the sulfur dioxide recovery process did not look favorable, and we did not feel justified in making the capital investment. Because of some new aspects in the situation, the prior development work was brought up to date in 1952, and several processes were piloted.

The results of this work demonstrated that the ammonium sulfite bisulfite system pioneered by The Consolidated Mining and Smelting Company of Canada, Ltd., offered the most promising solution to our problem. Representative of Olin Mathieson were sent to Trial, B.C., to evaluate further the application of the process, and eventually a licensing agreement was reached with Cominco. Modifications developed by Olin Mathieson were incorporated and a final design was obtained. In our Pasadena installation, this design has now operated for more than a year to yield an exit gas from the sulfuric acid plant containing less than 0.03% sulfur dioxide.

Scrubbing System

The system involves the use of a redwood scrubbing tower and a stripper for recovering the sulfur dioxide from the ammonium sulfite bisulfite solution. The upper section of the tower is separated from the lower section so that it is in effect a 2-stage unit. Absorbing solution is circulated in the top section to remove all but traces of the sulfur dioxide. Anhydrous ammonia is continuously added to the scrubbing solution as makeup for that which is converted to ammonium sulfate. The addition of water to the system maintains the solids concentrations at the optimum value for effective operation. The inert gases are discharged to the atmosphere from the top of the tower.

Exit gases from the acid plant containing sulfur dioxide, which formerly was discharged to the atmosphere, now enter the base of the new tower through a vestibule. Approximately 900 gpm. of scrubber solution circulate in the scrubber. The system is so designed that a minimum of ammonium sulfate is formed and a maximum of sulfur dioxide is removed from the gas stream. Solution is continuously bled from the scrubber to the stripper. Sulfuric acid is added to the stripper to convert the ammonium sulfite-bisulfite to ammonium sulfate and to assist in the evolution of sulfur dioxide. The exit gases from the stripper containing sulfur dioxide and air are returned to the acid plant drying tower for conversion to sulfuric acid. The solution from the stripper is pumped to an adjacent fertilizer plant as a 40% solution of ammonium sulfate.

How the System Operates

The scrubbing system was designed to handle sulfur dioxide concentrations as high as 0.9% and considerably higher concentrations for short periods. This capacity is particularly useful during plant startups and upsets. The overall efficiency of the unit is extremely high, and yields, as I have indicated, an exit gas containing less than 0.03% sulfur dioxide.

The system operates at low temperatures. Although the gases leaving the acid plant are at approximately 170°F., general cooling in the system, brought about by evaporation of water from the solutions, keeps the system at approximately 100°F.

Although the scrubbing system is very stable, care is taken to prevent excessive addition of ammonia. This would have the effect of producing greater amounts of ammonium sulfate, and could even cause severe loss of ammonia. Including handling losses, 97% of the ammonia is recovered as ammonium sulfate under normal operating conditions.

The scrubbing tower is oversize to hold the pressure drop to a minimum and prevent loss of production rate on the acid plant, a Leonard-Monsanto unit with a design of 400 tons/day.

Since the sulfur dioxide recovery system is provided with automatic controls, little attention from the acid plant operators is required, and no additional operating personnel is required. Since virtually all of the sulfur lost by an acid plant can be reclaimed by the use of such a scrubber, production increases as great as 20% may be realized on many units.

Extensive Research Conducted

In the initial stages of research, our goal was to reduce the sulfur dioxide to a very low level in the exit stack gases. It was imperative that the unit be so designed that it would, as far as could be anticipated, meet any new laws or regulations that might come into being. There have been many evaluations as to what level of contamination by sulfur dioxide is acceptable. A value of 0.2% sulfur dioxide has been set in some localities. There has been much discussion about concentration of 0.1% sulfur dioxide in the exit gases. It is possible with a single-stage Cominco sulfur dioxide recovery system to reduce the sulfur dioxide concentration in exit gases to 0.08%. With a 2-stage Cominco sulfur dioxide recovery system, it is possible to reduce the sulfur dioxide concentration in these same gases to less than 0.03%, which we feel will be more than satisfactory to any community.

Development of Recovery System

The recovery system was originally developed by Cominco to remove sulfur dioxide from smelter sintering gas, as is now being done at Trail. This led to the application of the recovery system to sulfuric acid plant tail gases, to which it is particularly well suited. We are presently studying the application of this process in the removal of sulfur dioxide from power plant stack gases. Results developed to date look very

* Presented at the Semi-Annual Technical Conference of the Air Pollution Control Association held at Houston, Texas, The Rice Hotel, Dec. 3-5, 1957.

promising. Successful development in this field offers tremendous possibilities.

Fundamentally, the Cominco sulfur dioxide recovery process finds application as a method for eliminating a pollution problem; however, in most cases, the economics are such that a long term payout on the investment will be realized. There are certain applications, such as in the case of our Pasadena acid plant, where the ability to operate at a high overload capacity has made the economics exceedingly favorable.

As a result of the successful operation of the ammonium sulfite bisulfite process at our Pasadena acid plant, our company representatives returned to Trail and negotiated with Cominco to become the exclusive licensing agent in the United States for the Cominco sulfur dioxide recovery process, including the modifications developed by Olin Mathieson.

Recovery of Chlorine from Air-Chlorine Mixtures*

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Cleveland, Ohio

. . . For those of you who may not be familiar with the term *snift gas*, it is a term that we use to describe the mixture of inert gases and chlorine which must be vented from a chlorine plant. The principal sources of *snift gas* are the vents from the main liquefaction unit and the vents from tanks of the air used in the transfer of chlorine. The concentration of chlorine in this air-chlorine mixture will vary in the range of from 20 to 50%. Chlorine of this concentration represents a real problem in disposal, and also represents an economic loss if it must be thrown away. The quantity of chlorine will represent between 4 and 8% of the total plant production. Similar vent streams occur in many chlorine consuming operations. For example, many chlorinations are completed only with the use of excess chlorine which must be vented. This chlorine can be recovered for refuse.

Chlorine producers and chlorine consumers are using, or have used, various schemes for the recovery or disposal of *snift gas*. One method is to reduce the concentration of chlorine in the chlorine-air mixture before disposal. This is most commonly achieved by condensing at low temperature or high pressure, or a combination of both. This process works in accordance with the principles of the perfect gas laws with the vapor pressure of chlorine being reduced by the low temperature and the partial pressure of chlorine in the air-chlorine mixture being further reduced by the high pressures. This results in liquefying or condensing additional chlorine. The resultant air-chlorine mixture is then disposed of.

Many different arrangements have been resorted to; the simplest, and one most commonly used, is to vent this material to the atmosphere through a pipeline located in some high point of the plant such as, an elevated water tower. If the wind blows in the proper direction or if large quantities of air are used to dilute the chlorine as it issues from the vent, this serves the purpose with a minimum of cause for complaints.

Another method which can be used successfully when conditions are correct is to absorb the residual chlorine in cold water. A packed tower is used in this process, and if the plant is located near a flowing stream, the resultant chlorine water can be disposed of with very little difficulty. However, the water from the tower is usually saturated with chlorine, and unless it can be run directly into a stream of flowing water it represents a disposal problem almost as bad as the weak gas.

A third process is the use of caustic or lime to react with the chlorine in the weak gas. The reaction will go substantially to completion with the use of excess caustic. However, unless one has use for the resultant sodium or calcium hypochlorite, disposal is a problem. Location near a large body of water or a flowing stream is essential. This presupposes that the flowing stream is already contaminated with industrial waste or sewage and the chlorine in the hypochlorite will be consumed by the biological oxygen demand of the water in the stream.

Other methods less commonly used are reaction with ferrous chloride to form ferric chloride followed by the reaction of ferric chloride with scrap iron to convert back to ferrous chloride. This process is only economical when one has use for the resultant ferrous or ferric chloride. Sulphur has also been used in a similar manner to form sulphur chloride. This process would only be used when one has a use for the resultant sulphur chloride. Sulphur chloride is probably more diffcult to dispose of than the waste chlorine.

In 1948, my company developed a process that provides for the complete recovery of all of the chlorine in the *snift gas* economically. The principle upon which this process operates, the differential absorption of chlorine in carbon tetrachloride followed by the recovery of the chlorine from the carbon tetrachloride by stripping, is very simple. The absorption takes place at a pressure of 100 psi., and the stripping at a pressure of approximately 35 psi. The stripping pressure chosen is the pressure normally carried on the main chlorine condensing plant, so that the recovered chlorine can be returned directly to the main stream of chlorine without further compression or pumping. The chlorine can be recovered as gas, or by the addition of a condenser in the flow sheet it can be recovered as a liquid.

At present, there are 3 of these recovery plants in operation. We have not installed the system at our other chlorine producing plants, since the chlorine consuming processes at these plants are such that a *snift* recovery problem does not exist. A typical recovery unit would have approximately these operating conditions:

A chlorine-air mixture containing 35% chlorine at a pressure of 10 psig. would be delivered to the suction of a positive displacement horizontal non-lubricated compressor. It would be compressed to 100 psig. pressure and would leave the compressor at a temperature of 240° F. The gas would be cooled first in a

* Excerpts from a paper at the Semi-Annual Technical Meeting of the Air Pollution Control Association, December 3-5, 1956, The Rice Hotel, Houston, Texas.

water-cooled and then in a refrigerated heat exchange. The resultant condensed part of the chlorine would be returned directly to the system.

The cooled gas, at a temperature of 5°F., containing approximately 30% chlorine, would enter the bottom of a packed column. The gas would flow upward in this column, being scrubbed by the counter-current flow of carbon tetrachloride entering at 0°F. The gas would then issue from the top of the tower through a back pressure controller completely stripped of chlorine. The carbon tetrachloride would leave the bottom of the column containing all of the recovered chlorine at a temperature of 50°F. An increase in temperature is due to the heat of solution in the carbon tetrachloride. The chlorine-rich solvent then flows to approximately the center of the stripping column. The lower section of the column functions as a stripper to strip the chlorine from the solvent. A thermosiphon reboiler is used at the bottom of the column to provide the heat necessary for stripping. The stripped carbon tetrachloride leaves the bottom of the column at 260°F., is cooled to 0°F. and is recycled to the top of the absorber. The upper section of the stripping column is the rectifying section; here the rising chlorine vapor is in contact with refluxing liquid chlorine and the resultant pure chlorine gas, free of the carbon tetrachloride solvent, issues from the top of the column for recovery. Part of the chlorine from the top of the tower is continuously condensed and refluxed to the tower. The balance can be condensed and recovered as liquid, or it can be returned as gas to the main chlorine plant or to a chlorine consuming process.

It is estimated that the operation of a typical recovery unit will provide for the recovery of chlorine as liquid at a total cost of approximately $19.00/ton. This compares to the current market price for chlorine in tank cars of $63/ton. All costs including operating costs and investment burden are included; however, these will vary from plant to plant.

Vertical Temperature Profiles in Relation to Other Meteorological Elements and to Air Pollution*

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Richland, Washington

Temperature profiles in the first 400 ft. above ground surface near Hanford, Washington are considered with respect to fog, sky condition, wind, and warm and cold air advection. The significance of each situation is discussed in regard to the accumulation and dispersal of air pollution. A case of inversion breakdown due to fog formation is considered and this type of situation is shown to be extremely adverse to effective diffusion of air contaminants. It is shown that, during lapse periods in summer, there is a tendency toward steeper lapse rates as the wind speed increases. The character, as well as the speed of the wind, is shown to be an important factor in consideration of nighttime temperature profiles. The features of cold and warm air advection are presented and their effectiveness in dispersal of air pollution is considered.

Temperature Profiles In Relation To Stack Effluent Flow Patterns

There are 5 main types of stack effluent flow patterns. As shown in Fig. 1, each type is related to a certain vertical temperature structure in the lower atmosphere.

1. *Looping.* Looping (shown photographically in Fig. 2A) occurs with superadiabatic lapse rates. Although sporadic puffs having relatively high concentration reach the ground near the stack during light winds, diffusion in most cases takes place both above and below stack-top and dangerous accumulation of air pollutants does not ordinarily occur.

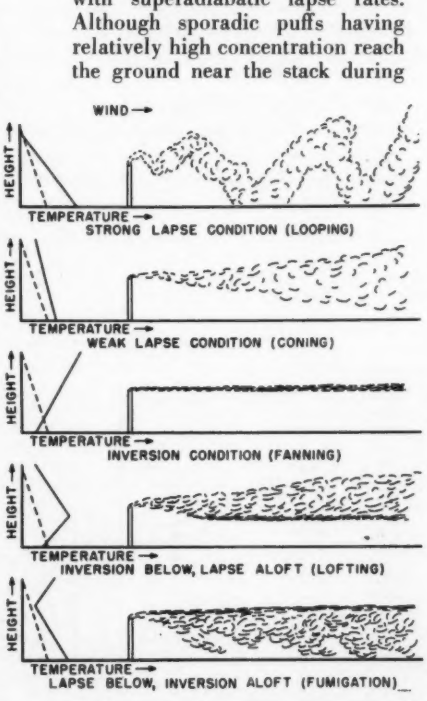

Fig. 1. Schematic representation of stack gas behavior under various conditions of vertical stability. ...., dry adiabatic lapse rate.

2. *Coning.* Coning occurs with a temperature gradient between dry adiabatic and isothermal. Because of less thermal turbulence, the effluent reaches the ground at a greater distance from the stack than in the case of looping and hence is usually more dilute. Coning is favored by cloudy and windy conditions.

3. *Fanning.* Fanning (shown photo- temperature inversions. Due to a relatively log degree of turbulence, concentration within the plume is high. This produces higher concentrations at greater distances from a stack than any other type of flow pattern. However, since a fanning-type plume rarely if ever reaches the ground within 15 miles if emitted from an elevated source, it is generally considered favorable for stack releases.

4. *Lofting.* Lofting occurs with an inversion below, lapse above, type of situation. In lofting, effluent does not usually penetrate to the ground near the stack. However,

* Presented at the East Central Section Meeting of the Air Pollution Control Association, September 17, 1956, at Columbus, Ohio.

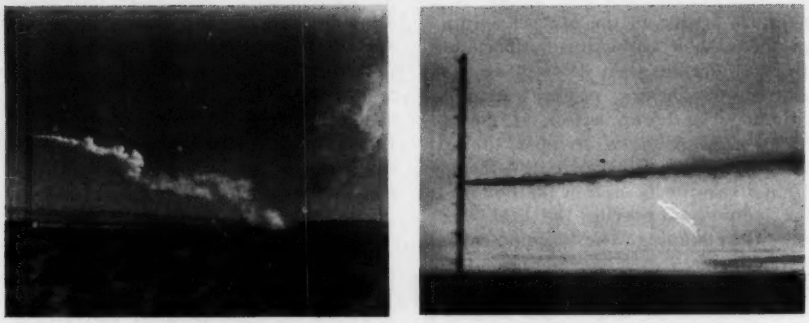

Fig. 2. Two types of stack effluent flow patterns. A. Looping. B. Fanning.

Explanation of Symbols Used In Fig. 3, 5, and 9

Sky:—

○ Clear ....0.0 sky cover

⊖ †Scattered clouds....0.1 to 0.5 sky cover

⊜ †Broken clouds ....0.6 to 0.9 sky cover

⊕ †Overcast .....Ten-tenths sky cover

× Sky obscured..Ten-tenths of sky hidden by precipitation or by surface-based obstructions to vision.

−× Sky partially obscured .0.1 to 0.9 of sky hidden by precipitation or by surface-based obstructions to vision.

†A minus sign prefix denotes that the clouds are thin. Number prefix denotes height in hundreds of ft.

Ceiling†--

E—Estimated.

W—Indenfinite. This classification pertains to ceilings obtained when a surface-based obscuring phenomenon, such as fog, is present. The height ascribed to such a ceiling is an estimate of the vertical visibility into the obscuring phenomenon.

†Ceiling is the height ascribed to the lowest layer of clouds or obscuring phenomena that is reported as broken, overcast, or obscured.

Weather or Obstructions to Vision:

F—Fog.

T—Thunderstorm.

RW—Light rain shower.

there is a zone of relatively high concentration near the top of the inversion layer. Because of diffusion aloft with little likelihood of the effluent reaching the ground, lofting is considered favorable for *dumping*. This situation occurs most often near sunset.

5. *Fumigation*. Fumigation occurs with lapse below, inversion aloft, type of situation. This is the most unfavorable situation for stack emission since the inversion aloft prevents diffusion upward and effluents come to the ground along the entire length of the plume. Concentrations near the stack are appreciably higher than in looping or coning. Fumigation occurs most often shortly after sunrise.

Fog and Low Stratus

The formation of fog frequently results in a drastic alteration of the temperature structure in the lower atmosphere. This alteration is most notable if a nocturnal inversion is present at the time. Fig. 3 shows (1) the intense inversion existing shortly before the time of one case of fog formation, (2) partial breakdown of the inversion shortly afterward, and (3) complete breakdown in the first 400 ft. above ground surface within 3.7 hr. The table at the lower left of Fig. 3 shows the inversion breakdown resulting from a combination of warming near the ground surface and cooling at all higher levels within the fog layer.

Fog which forms during the presence of a nocturnal inversion does not, in all cases, alter the temperature profile in the manner noted above. Ground fog, for example, seems to have little or no effect on an inversion. However, in any case where fog becomes sufficiently thick and deep as to obscure the sky, a breakdown of any inversion within the fog layer is very likely.

Stack emission during and after the formation of fog can result in serious air pollution. First, there is the possibility of fumigation as the base of the inversion raises to stack-top level. Then, as the base of the inversion raises above stack top, the *inversion lid* puts a ceiling on upward diffusion and stack fumes spread to the ground as shown in Fig. 4. Subsequent diffusion may be slow due to low wind speeds which are typical of such situations. In any case, if valley walls of sufficient height are

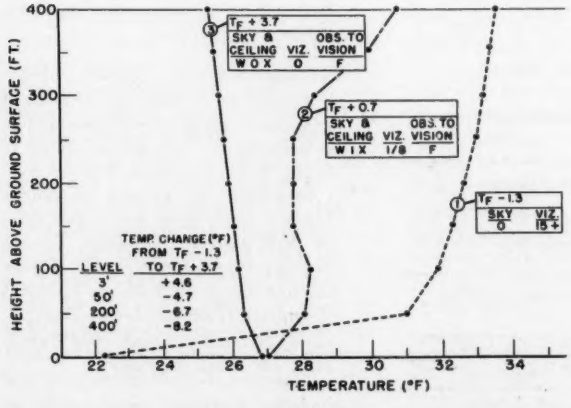

Fig. 3. Vertical temperature distribution at selected times before and after fog formation: 9 December, 1947. TF denotes time fog was first observed at the station (2020 PST). Other times are relative to TF and are given in hours.

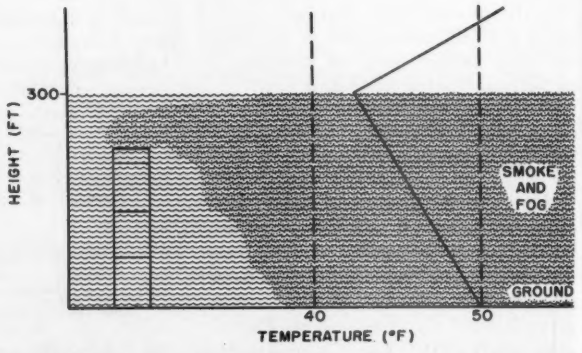

Fig. 4. Schematic representation of stack gas behavior during fog with inversion lid above fog layer.

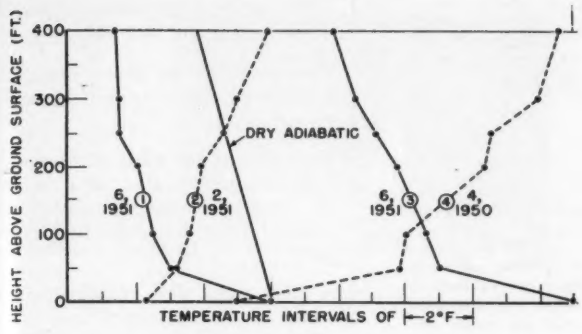

Fig. 5. Temperature profiles in relation to sky condition.

....., daytime profiles observed at 1530 PST.

....., nighttime profiles observed at 0330 PST.

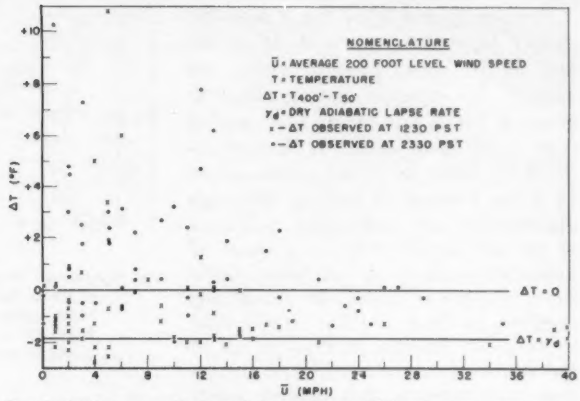
NOMENCLATURE
Ū = AVERAGE 200 FOOT LEVEL WIND SPEED
T = TEMPERATURE
ΔT = T400' − T50'
γd = DRY ADIABATIC LAPSE RATE
x — ΔT OBSERVED AT 1230 PST
• — ΔT OBSERVED AT 2330 PST
ΔT (°F)
ΔT = 0
ΔT = γd
Ū (MPH)

Fig. 6. Scattergram of vertical temperature difference vs. average wind speed observed at selected times during January 1952. 1953.

present, all diffusion must be contained within the confines of these walls and the inversion lid. Polluting of this entrapped air presents serious dangers to both plant and animal life and, in extreme cases, has resulted in notorious disasters. Examples are the syndromes of Liege, Belgium in 1930 [1]; Donora, Pennsylvania in 1948 [1, 2, 3]; Poza Rica, Mexico in 1950 [4]; and London, England in 1952-53. [5]

The meteorology reported in connection with the above incidents indicates that fog was a major contributing factor to all of them. However, the reports postulate the existence of a temperature inversion throughout the layer of fog. Observations taken in fog at Hanford do not confirm this hypothesis. Referring to Fig. 3, however, the shape of profile ② and the contents of the table at the lower left both strongly indicate the presence of an intense inversion (inversion lid) which the Donora investigation [2] postulates immediately above the fog layer. The existence of an inversion lid is also implied theoretically in the work of Fleagle, Parrot, and Barad [6] who show mathematically that the temperature within a turbid layer decreases with height and time and approaches the minimum possible at the top of the layer.

Another important aspect of the *inversion lid* situation is its tendency to persist. Observations taken at Hanford show that, during an entire period of thick fog, there is essentially no change, diurnal or otherwise, in the lapse rate in the first 400 ft. above ground. At the same time, reflection and radiation at the top of the fog layer probably maintains, or even intensifies, the strength of the *inversion lid*.

Temperature profiles observed at Hanford during periods of low stratus overcast do not differ importantly from those observed in fog. In both cases, the lapse rate in the 1st 400 ft. above the ground is approximately dry adiabatic with practically no diurnal variation. In low stratus, however, the inversion lid is higher than in fog and hence the volume available for diffusion is greater. Nevertheless, diffusion is still restricted to an important extent and industrial pollution during low stratus poses the same problems as in fog.

Sky Condition

Fig. 5 shows a set of 2 nighttime and 2 daytime temperature profiles. Each set has one profile observed under essentially clear sky and one observed under essentially overcast sky. In all 4 cases, dates are near the same time of season and wind speeds are light.

(1) H. H. Shrenk, Causes, Constituents and Physical Effects of Smog Involved in Specific Dramatic Eposides. *Arch. Ind. Hyg. and Occup. Med.* **1, 2, 189-194** (February, 1950).

(2) H. H. Shrenk. Air Pollution in Donora, Pa. *Public Health Bull.* No. 306, (1949).

(3) Clarence A. Mills, Comments and Communications (The Donora Episode). *Science,* Vol. 3, 67-68. (January 20, 1950).

(4) Louis C. McCabe and George D. Clayton, Air Pollution by Hydrogen Sulfide in Poza Rica, Mexico. *Arch. Ind. Hyg. and Occup. Med.* **6,3 199-213** (September, **1952**).

(5) An Editorial: Deaths During the Severe Fog in London and Environs, December 5 to 9, 1952. *Arch. Ind. Hyg. and Occup. Med.* **7, 4, 275-276** (April **1953**o.

(6) R. G. Fleagle, W. H. Parrott and M. L. Barad, Theory and Effects of Vertical Temperature Distribution in Turbid Air. *J Meteorol.* **9, 1, 53-60** (February, **1952**).

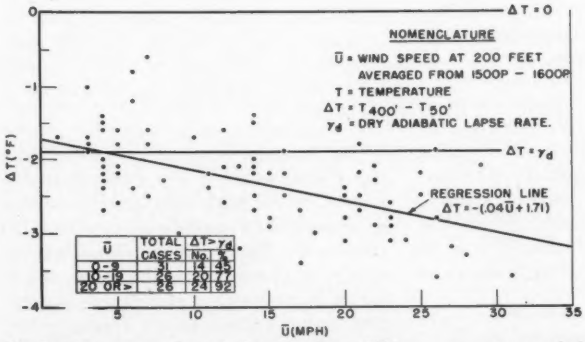
ΔT = 0
NOMENCLATURE
Ū = WIND SPEED AT 200 FEET AVERAGED FROM 1500P − 1600P
T = TEMPERATURE
ΔT = T400' − T50'
γd = DRY ADIABATIC LAPSE RATE.
ΔT = γd
REGRESSION LINE
ΔT = −(.04Ū + 1.71)
ΔT (°F)
Ū (MPH)
Ū | TOTAL CASES | ΔT > γd No. | %
0 - 9 | 31 | 14 | 45
10 - 19 | 26 | 20 | 77
20 OR > | 26 | 24 | 92

Fig. 7. Scattergram of vertical temperature difference vs. average wind speed observed at 1530 PST during June, 1950, and at the same time on subsequent June days where Ū satisfied the criteria: 1951-1952. Ū < 5 mph. or > 10 mph. 1953-1955. Ū < 5 mph. or >20 mph.

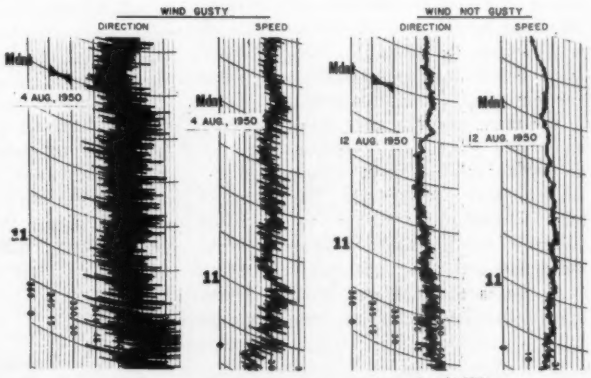

Fig. 8. Two types of wind character under similar conditions of speed and direction.

Profiles ① and ③ of Fig. 5 show the steeper lapse rates, particularly in the first 50 ft. above ground, which can usually be expected during daylight hours if the sky is clear. The looping type of effluent pattern is characteristic of ③, while in ① the pattern might be either looping or coming. Although appreciable and widespread pollution of the air might occur as a result of industrial activity or of large forest fires, dispersion under the conditions depicted in these profiles is still relatively good. Absence of some or all of the factors associated with air stagnation contributes to this relative safety from extreme pollution such as occured at Donora in 1948.

In either looping or coning conditions, dilution of the containment which comes to the ground near the source depends mainly on the wind speed. However, experiments by Church [7] indicate that, for any given speed, the maximum concentration within a puff increases with increasing instability until a certain critical value is reached. Any increase in instability beyond this critical value results in lower puff concentrations. It is probable, therefore, that highest puff concentrations can be expected when the wind speed is low and the lapse rate is less steep than in ③ of Fig. 5.

Profiles ② and ④ of Fig. 5 show a more intense nocturnal inversion under high thin cloudiness than under clear skies. While this may not always be true, observations indicate that high thin cloudiness is not an inhibiting factor in either the formation or perpetuation of an inversion. In fact, it appears that the thermal structure of the lower atmosphere in the presence of high thin cloudiness is essentially the same as would be observed if the sky were clear.

A contaminant released into the air under inversion conditions such as those depicted in ① and ③ of Fig. 5, tends to flow downwind at the level of emission. While this is generally favorable for emission from elevated sources, it is the most adverse meteorological condition for release of contaminants, such as hydrocarbons from automobile exhausts, near the ground. The automobile is recognized today as a major source of air pollution in densely populated districts. For example, the Stanford Research Institute [8] has found that under low inversion conditions in

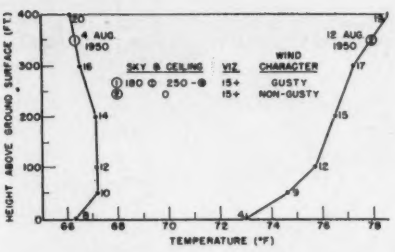

Fig. 9. Vertical temperature profiles observed at 2330 PST: 4 August vs. 12 August, 1950. Wind speeds (mph. averaged from 2300 PST to 2400 PST) are shown adjacent to the plotted points.

Los Angeles automobile traffic can result in average concentrations of automobile exhaust amounting to 140 ppm. or more in the air. By *low inversion* it is assumed that the Institute is referring to the *inversion lid* situation which, however bad, is still more favorable than the surface inversion.

Wind Speed

In Fig. 6 and 7 the average 200 ft. level wind speed ($\bar{U}$) is plotted against the instantaneous temperature difference (ΔT) between the 400 ft. and 50 ft. levels. In all cases ΔT is measured on the half-hour while U is averaged over the 1 hr. period beginning one-half hour before the time of the ΔT observation.

The distribution of points shown in Fig. 6 is considered to be representative for winter months. It is seen that during both the 1230 and 2330 observations ΔT may have a wide range of values with low values of $\bar{U}$. As $\bar{U}$ increases, however, the range in ΔT becomes less and, at values of $\bar{U} > 20$ mph., most of the corresponding values of ΔT fall between the lines $\Delta T = 0$ and $\Delta T = \gamma d$. It is particularly noteworthy that, with low values of $\bar{U}$, ΔT may assume large positive values (representing strong inversions) near midday. This anomalous condition will be discussed in connection with warm air advection.

The distribution of points shown in Fig. 6 is also an accurate portrayal of $\bar{U}$ vs. ΔT relationships observed during nighttime hours of summer. However, when the distribution during summer daylight hours is examined (Fig. 7) a significantly different distribution is noted. The most noteworthy features of Fig. 7 are:

1. There are no inversions—all points falling below the line $\Delta T = 0$.
2. The scatter in the points does not decrease significantly as $\bar{U}$ becomes greater.
3. As shown by the table at the lower left, the greater the value of $\bar{U}$, the greater is the percentage of points falling below the line $\Delta T = \gamma d$.
4. A regression line (indicating a tendency toward steeper lapse rates with increasing wind speeds) may be fitted to the plotted points.

Fig. 6 indicates that, except for daylight hours in summer, no accurate assumption regarding the temperature profile or effluent flow pattern can be made unless the wind speed is approximately 20 mph. or greater. If the speed does exceed 20 mph. there is a high probability of a coning-type pattern. Such a situation is symbolic of a high dilution rate and in most cases would be favorable for stack emissions.

Fig. 7 indicates that, during summer daylight hours, the looping type effluent pattern may be associated with higher wind speeds than is generally believed. However, it must be emphasized that some non-meteorological factors, such as terrain, probably contribute to some of the features of Fig. 7. Hence, these features may not hold true for all geographic locations.

Wind Character

The character of a wind is determined by the amount of gustiness present. Although gustiness is generally considered to increase with speed, this is not always true. Two entirely different types of wind character under similar conditions of speed and direction are shown in Fig. 8. Diurnal and seasonal influences are held to a minimum by considering winds observed at the same time of day on nearby dates. The mean wind in the 2 cases is approximately NW 20 mph. in each. The gustiness, however, is much more pronounced in one case than in the other.

Temperature profiles associated with the 2 wind cases of Fig. 8 are shown in Fig. 9. Some high thin cloudiness was associated with profile ① but, as has previously been noted, cloudiness of this type is not an inhibiting factor as far as inversions are concerned. It therefore seems reasonable to conclude that the difference in the shape of profiles ① and ② is largely a result of the difference in character of the wind associated with them.

[7] P. E. Church, Dilution of Waste Stack Gases in the Atmosphere. *Ind. Eng. Chem.* **41, 12, 2753-2756** (December, **1949**).

[8] Stanford Research Institute. The Smog Problem in Los Angeles County. A report on the nature and causes of smog (January 1954).

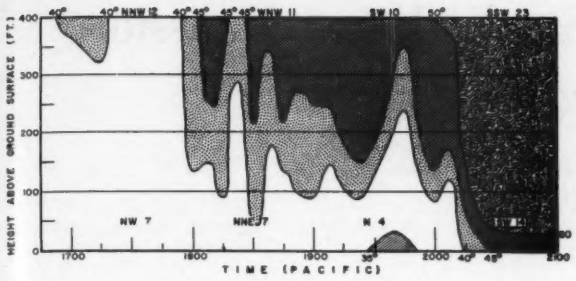

Fig. 10. Vertical temperature structure during a period of warm air advection: 18 January, 1953.

The relation of gustiness to other meteorological parameters has also been recognized at Brookhaven by Singer and Smith[9]. The authors find that gustiness is closely related to the temperature profile but that its association with wind speed is less distinct. They also find their *type D* gustiness classification (where the direction trace approximates a line) is sometimes associated with wind speeds above 25 mph.

Fig. 9 shows that, during nighttime, the speed of the wind is not infallible as an indicator of effluent flow-pattern type. In spite of the very weak surface inversion associated with profile ①, mechanical turbulence can be sufficient to cause stack effluents to come to the ground in a coning-type pattern. In spite of almost identical wind speeds, except near the ground, fanning is the only type of effluent pattern which can be associated with profile ②.

Advection

Cold Air Advection

The onset of advective cooling at Hanford does not usually produce any significant changes in the temperature profile. However, one aspect of this type of cooling is worthy of note. When a cold front passes Hanford, the air mass behind the front usually has the Pacific as its source region. Even though the air being displaced is seldom polluted sufficiently to reduce visibility below 15 miles, the new air is nevertheless significantly cleaner and the records of solar radiation sometimes reveal it. For example, radiation received on June 27 and 28, 1956 amounted to 706 and 760 langleys, respectively. Both days were clear, but a cold front passed the station at 1745 PST on the 27th. Except for the change in air masses, there appears nothing to account for the nearly 10% greater radiation on the 28th. For locations subject to invasion of maritime air masses, these invasions can provide a useful mechanism for the removal of polluted air.

Warm Air Advection

The onset of advection warming at Hanford is signaled by a rise in temperature at the top (400 ft.) level of the meteorology tower. Thereafter the warm air works slowly and erratically to the surface, producing large inversions which usually last for several hours and occasionally for several days. Typical of such a case is that shown in Fig. 10. Here, the first sign of warm air advection is the temporary appearance of a 40° isotherm at 400 ft. near 1700. The warm air did not reach the surface, however, for more than 3 hr. afterward. In the meantime the lowest surface temperature and strongest inversion occured near 1945, less than one-half hr. before the warm air reached the surface.

Distinctive features of the advective inversion are:

1. They occur as a result of warming from above and build downward. Nocturnal inversions which normally occur in the absence of appreciable winds or cloudiness result from radiational cooling near the ground and build upward.
2. They tend to be more intense than radiation inversions. In the latter, the temperature at 400 ft. is rarely as much as 15° higher than at the surface and during 12 years of record has never been more than 19° higher. In the advective inversions, on the other hand, surface vs. 400 ft. temperature differences exceed 15° quite frequently and have been as great as 28°
3. There is no diurnal limitation on the time of formation or decay. It has been noted previously that, during low wind speeds in winter, intense inversions may sometimes be present at midday. Such inversions are invariably of the advective type. Radiation inversions never form much earlier than sunset and never persist for any great length of time after sunrise.
4. At Hanford, they occur only during the cold season. Radiation inversions, on the other hand, may occur during nighttime in all seasons.

During nearly the entire period of an advective inversion, a fanning type of effluent flow pattern can be expected from a stack of 200 ft. or higher. However, Fig. 10 suggests the possibility of fumigation during brief intervals as the base of the inversion raises and lowers. There may also be the problem of a low-level inversion lid before the inversion extends to ground surface. However, this problem is not likely to persist for any great length of time as in the case of air stagnation.

When a warm front passes Hanford, the air mass behind the front usually is imported from the Pacific. Hence, as in the case of cold fronts, it is reasonable to believe that cleaner air may result. Although this might be true, the invariable cloudiness at such times precludes the possibility of verification by recourse to the records of solar radiation. At any rate, the wind which nearly always follows the passage of a warm front creates a favorable condition for most stack emissions.

Summary

Fog in combination with atmospheric stagnation is characterized by a lapse condition from the surface to the top of the fog layer and by an intense inversion immediately above. This is the most unfavorable meteorological situation for industrial pollution of the air. An inversion extending from the ground upward for several hundred feet favors release of contaminants from elevated sources but not from the ground. Such an inversion tends to occur only at night but, in the case of warm air advection, may occur at any time. Temperature profiles identified with looping and fanning, although commonly associated with low wind speeds, may occur at speeds of 25 mph. or more.

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[9] I. A. Singer and Maynard E. Smith, Relation of Gustiness to other Meteorological Parameters. *J. Meteorol.* 10, 2, 121-126 (April, 1953).

Air Pollution Control of Smoke House Emission in the Packing Industry*

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There are over 35 packing houses in Los Angeles, Calif., discharging an estimated 3,000,000 ft.³/hr. of smoke house effluent into the atmosphere. This gas stream contains some 650-700 lb. of particulate matter. In late 1955 several packing houses were cited under Rules 50 and 53B of the Los Angeles County Code.

> For discharge of smoke in excess of 3 min./hr., the following rules apply:
>
> *No discharge with more than 0.2% of sulphur compounds by total volume, or with more than 0.4 gr. of combustion contaminants/ft.³ of gas, based on 12% carbon dioxide content. No discharge of opacity greater than about 40% (No. 2 shade on a U. S. Bureau of Mines Ringelmann Chart).*

To meet these standards every smoke house must have some type of air pollution control equipment.

Smoke houses are generally fired by two methods—direct gas fired, or steam fired. Temperatures and humidity are controlled in the houses by the addition of outside tempered air. Smoke is generated by damp smouldering sawdust and is introduced into the top of the house. Ninety percent of the smoke is continuously recirculated, with 10% being vented to atmosphere. This 10% must be handled by the collection system. See Fig. 1.

* Presented at the 49th Annual Meeting of the Air Pollution Control Association held at Buffalo, N. Y., May 20-4, 1956.

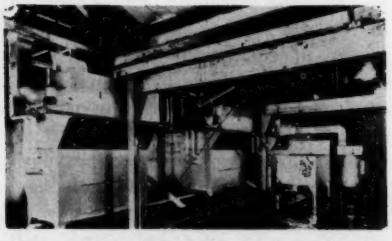

Fig. 1. Blower-Heater and Smoke Generating Equipment (Tipper)

In February of 1955 an equipment manufacturer was contacted by Luer Packing Company and asked for recommendations on equipment to solve the problem. Previous data gathered from smoke houses showed that steam and gas fired houses had an average particulate grain loading of 0.3 to 0.4 gr./scf. The CO_2 content was reported to range from 1 to 2% for steam fired house and approximately 3% for gas fired houses. Previous smoke abatement studies included water scrubbing, filters and bag houses, electric precipitation, 100% incineration and catalytic incineration. Some of the methods were not efficient enough and others were either too costly or too difficult to maintain. With previous success in the use of combined high efficiency hydrostatic and low voltage electrostatic collectors, Fig. 3 and 4, on such problems as asphalt saturators, oil fumes from quenching and heat treating and shale oil refining, a pilot size electrostatic collector was installed to check the electrical resistivity of the effluent. This equipment was observed by the Los Angeles County Air Pollution Control Board and a permit to construct was granted to Luer Packing Co.

A Type W Roto-Clone wet type dynamic precipitator and a low voltage electrostatic collector was installed to handle 12000 cfm. See Fig. 2 & 3. The Roto-Clone functions as induced draft fan, a primary particulate matter collector and conditioner for the gas to decrease its resistivity. A centrifugal water eliminator was installed ahead of the electrostatic to prevent any free moisture carry over. A unique recirculating and damper arrangement was designed into the system to prevent upsetting the balance on the smoke houses. See Fig. 4.

When placed in service, moisture from condensation accumulated on the insulators and plates, causing excessive arcing of the plates and allowing the voltage to leak across the insulators. To prevent this, a steam coil and regulator was installed ahead of the electrostatic, raising the effluent gas temperature to approximately 170°F.

This installation being the first of its kind to be applied to smoke houses in

Fig. 2

Los Angeles County, the initial tests were conducted by the Research Division of the Air Pollution Board. Two tests were run. (See Table I—Tests 1 and 1A).

Tests 1 and 1A had such a low CO_2 reading that is was almost impossible to measure by the Orsat method. With this low reading, making the correction to 12% CO_2, the outlet grain loading multiplier is 60. Test 1A showed a lower inlet but higher outlet loading than Test 1. It is believed that some of the material collected during Test 1 was volatilized by the high temperature in the housing of the electrostatic. During the test run the opacity was very acceptable ranging from 0-10%, depending upon operation of the smoke houses. See Fig. 5 and 6.

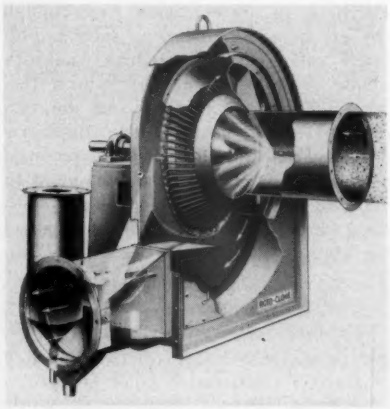

Fig. 3

TABLE I
Field Test Data

Test	Sampling Method (Note 1)	Inlet Gr. Loading (Gr./ Scfm.)	Outlet Gr. Loading (Gr./ Scfm.)	% CO_2 0.20	Outlet Gr. Loading corrected to 12% CO_2	System Efficiency	Ionizer & Plate Voltages	Discharge Temperature	Opacity %	Process
1	Greenburg-Smith Impinger in ice bath followed by Watman Thimbles	0.139	0.029	0.20 Orsat Analysis	1.62	78.3	9500-4500	171° F.	10	Five houses smoking No product in houses
1A	Greenburg-Smith Impinger in ice bath followed by Watman Thimbles	0.086	0.041	0.182 Orsat Analysis	2.46	52.3	11000-5500	169° F.	10	Four houses smoking Two houses cooking
2	Greenburg-Smith Impinger in ice bath followed by Millipore filter	—	0.0548	0.0294 Gravametric Analysis	3.62	—	11500-5500	105° F.	0-5	Seven houses smoking No product in houses
2A	Greenburg-Smith Impinger in ice bath followed by Millipore filter	— (Note 2)	0.0306	0.117 Gravametric Analysis	12.5	—	11000-5000	100° F.	0-5	Two houses cooking only
3	Greenburg-Smith Impinger in ice bath followed by Millipore filter	— (Note 4)	0.00948	0.117 Gravametric Analysis	0.973	—	12000-6000	100° F.	0	Four houses smoking Product in houses
3A	Millipore Filter Paper (Dry test)	0.0329 (Note 3)	0.0033	0.20 Gravametric Analysis	0.338 (Note 5)	90.5	12000-6000	100° F.	0	Four houses smoking Product in houses
3B	Greenburg-Smith Impinger in ice bath followed by Millipore filter	—	0.0078	Assumed	0.468	—	12000-6000	100° F.	0	Four houses smoking Product in houses
4	Greenburg-Smith Impinger in ice bath followed by Millipore filter	— (Note 7)	0.00652	0.116 Gravametric Analysis	0.675	—	12000-6000	106° F.	0	Four houses smoking Product in houses
4A	Greenburg-Smith Impinger to 60° F.	—	0.0142	0.116 Gravametric Analysis	1.53	—	12000-6000	106° F.	0	Four houses smoking Product in houses
4B	Millipore Filter Paper (Dry test)	0.103 (Note 6)	0.00153	0.116 Gravametric Analysis	0.167 (Note 5)	98.5	12000-6000	106° F.	0	Four houses smoking Product in houses

NOTES:

NOTE 1: Test 1 and 1A conducted by Research Division Los Angeles County Air Pollution Control Board. All other tests conducted by independent testing laboratory. all other tests conducted by independent testing laboratory.

NOTE 2: Cooking cycle rules not a combustion process and not subject to Rule 53B Air Pollution Code.

NOTE 3: Sampler broke down about 2/3 way through test.

NOTE 4: Alkali sprayed in inlet of Type W Roto-Clone.

NOTE 5: Even though outlet grain loading passed Rule 53B, test procedure not approved by Los Angeles County Air Pollution Control Board.

NOTE 6: System efficiency 93% including vapor state

NOTE 7: Double ionizer installed.

During the test cycle several difficulties were encountered; high humidity, low ionizer and plate voltage, and vaporization of previously collected material. It was felt that the items contributed to the non compliance with the air pollution requirements.

Before having another series of tests run, it was decided to make several changes in the test procedure. Millipore filter paper was substituted for Watman Thimbles, (Millipore paper has higher collection efficiency $\frac{1}{2}$ μ particles and smaller), in the impinger train and Gravametric Analysis made on the CO_2 content. Several changes were also made in the operation of the equipment. A separate test was run on the cooking cycle to determine its effluent. Since the cooking cycle was to be separate, the discharge temperature was kept as low as possible. The steam coil was used only to keep the dry bulb temperature slightly above the dew point. The results of these tests are shown in the Table Test 2 and 2A.

The CO_2 content of Test 2 was lower than the previous test and the CO_2 multiplier had now risen to 65 times the outlet grain loading. During the test cycle it was noticed a small amount of gas was by-passing the electrostatic by leaking between the plates and the side panels.

The Los Angeles County Air Pollution Control Board ruled that the cooking cycle was not a combustion process and that Rule 53B did not apply. On the basis of this, the cooking cycle could be vented to atmosphere, even though the corrected grain loading was 4 times that of the smoking cycle. With the cooking cycle removed, the previous difficulties, due to moisture condensation, were eliminated.

From an analysis of Test 1, 1A, 2 and 2A, it was believed that possibly much of the material being caught in the Greenburg-Smith impingers is in the vapor phase and was being condensed in iced impinger train. To check this theory, Tests, 3, 3A and 3B were run. On Test 3, an iced impinger train was used and Test 3B was run on a dry weight basis using Millipore filter paper. Test 3B was run as a check on Test 3. A suggestion was made by a chief chemist to spray an alkali into the inlet of the Type W to possibly absorb some of the aldehydes. This spray was incorporated on Test 3.

The third series of tests were the first ones run with any product in the houses. From the much lower grain loading than previously recorded, it is evident that the product absorbs a considerable quantity of smoke. The CO_2 content was even lower than before, raising the outlet grain loading multiplier to 102. Comparing Test 3 and 3B, the efficiency was improved little, if any, by the addition of the alkaline spray. The low pH of the impinger sample also indicated the alkaline spray was of little value.

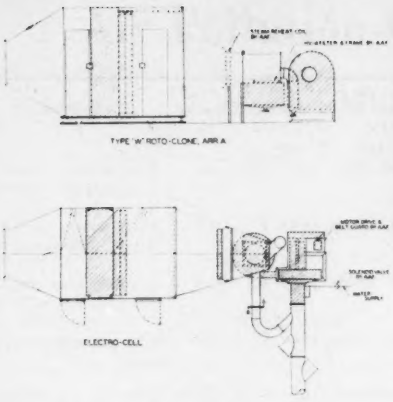

Fig. 4

On the basis of the dry weight method, the outlet grain loading was lower than the maximum allowed under the law; however, this method of testing was not approved. The overall system efficiency, dry weight method, was 90.5% and would have been higher if the sampling apparatus had not broken down about ⅔ of the way through the test.

Although the grain loadings by the Greenburg-Smith impinger method, were much lower than previous test, they were still above the allowable emission rate. Approximately 0.005 to 0.006 gr./scfm. are in the vapor state which the electrostatic is unable to capture.

Under existing regulations the results of all analysis and tests are to be calculated or reported at a temperature of

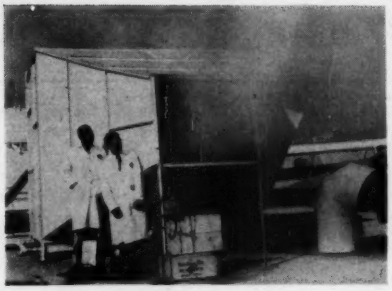

Fig. 5

60°F. Because the dry weight method was not approved, it was decided to run another series of tests holding the impinger train temperature as close to 60°F. as possible. Using this method it was thought that possibly not as much material would condense in the impinger train. At the same time another dry test was run to collaborate the findings in Test 3A.

In an effort to improve efficiency another ionizing section was installed ahead of the electrostatic. Little if any improvement was noted. See Tests 4, 4A, 4B data.

Conclusions

Studies to date have demonstrated:

1. Combination of wet type dynamic precipitator and low voltage electrostatic, will reduce opacity of smoke house effluents from 0 to 10%; closer to 0 opacity under most conditions.

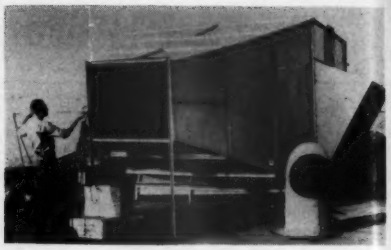

Fig. 6

2. Equipment will remove from 95 to 99% by weight of all solid contaminants existing at exit gas temperatures. Efficiency reduces to 90 to 93% range with wet impinger sampling when vapors are further condensed to 40° F. gas temperatures.

3. Treatment of the smoke house as a combustion process necessitates cleaning to an unusual high degree. Resultant low CO_2 concentrations means level of acceptable solids is 1 to 2% that of acceptable solid concentration from more conventional combustion processes.

4. Increasing CO_2 content by gas firing methods as opposed to steam firing permits allowable exit concentration 3 to 4 times greater although contaminants, quantities, characteristics and process exhaust volume is of the same order.

Modification to the Fontana Open Hearth Precipitators*

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An increasing amount of interest has been displayed by industry in the problem of air pollution control of the various industrial operations in this country. It seems to be a basic consideration that clean air is still one of the freedoms remaining, and to this end the metallurgical industries have been developing methods to control and police air pollution problems as they develop.

The Kaiser Steel Corporation plant is situated in an area that has long been highly conscious of its air pollution problem. The company has been engaged in a comprehensive study of this problem for many years.

San Bernardino County, in which the Kaiser Steel Corporation is located, is adjacent to Los Angeles County and has recently completed the formation of an Air Pollution Control District.

As a part of their continuing efforts in air pollution control, the problem of control for open hearth stacks was studied by the Kaiser Steel Corporation as early as 1943. Ten years ago the methods of developing accurate data on which to base collection and control equipment design were sketchy and indefinite. Further, the problem had not been studied regarding equipment design and selection because no installation had been completed up to that time.

Since then the Air Control and Research Department of Kaiser Steel has prepared numerous studies and reports on cause and effect of various stack emissions discharged to the atmosphere. Kaiser Engineers coordinated design data with these studies to complement the research phase of the overall program. This provides an excellent development and engineering program and permits the coordination of research to engineering design of the various collection and control devices.

The nine 225 ton open hearth furnaces have received the major share of attention, as the metallurgical fume emitted is extremely fine and colored. Dry electrostatic precipitators are now operating or in process of construction on all furnaces (Fig. 1).

The proposed vessels for the oxygen converter process to be installed shortly at Fontana also will be equipped with dry precipitators.

This paper will deal with some of the problems of design and with the construction of and modifications to the precipitators as installed on No. 3 furnace. The installation of the precipitators at Fontana has its roots in No. 3 precipitator.

The precipitators are designed to process under normal conditions about 74500 scfm. at 650° F. and 29.92 in. Hg., having an inlet grain loading of .53 gr./ft.^{3} at 650° F. All precipitators follow waste heat boilers.

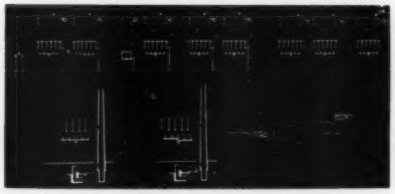

Fig. 1. Schematic drawing of precipitators on 9 open hearth furnaces. Larger drawings of precipitators No. 1, No. 2, show by-pass arrangements.

One of the interesting points of this installation is that it is possible to bypass the waste heat boiler to the stack, or bypass the precipitator to the stack, or to bypass both units and go directly to the stack.

The problem of maintaining constant furnace pressure under varying stack loads was solved through the use of Askania type control. No operating problems developed with the furnaces on which precipitators have been mounted.

Early studies developed that the basic criteria as to gas volume and dust loading was correct. Early test data indicated that the erratic gas loading of the precipitator together with the varying characteristics of the fume must be carefully considered in the design of any future units.

Operating problems were carefully studied for approximately 9 months. Pilot units were installed to determine why the prototype would not function as designed. These tests indicated that the following important operating problems required correction:

1. The vibration and shaking within the unit caused by movement of cranes, trains, and other heavy equipment in the open hearth building. This required strengthening and reinforcing of the precipitator and supporting structure.
2. The turbulent and erratic flow of gas entering the precipitator. Gas distribution was improved by modifications of design of the gas distributing devices within the precipitator proper.
3. Insufficient residence time of gas within the precipitator.
4. Low voltage and inadequate control of the connected energy to the discharge electrode system.
5. The sequence and type of rapping which permitted excessive dust build-up.
6. Automatic power control was needed to maintain voltage in the precipitator very close to the sparking potential during the varying conditions of the fume in the unit.

Each of these items may be considered as having a major bearing on the design of equipment for collection of the fume of the type encountered with a hot metal open hearth furnace.

Following the basic intent of conserving floor space wherever possible, and yet providing a trouble-free operating installation, the roof area of the open hearth shop adjacent to the stacks was selected as the best space for installation (Fig. 2).

The original design of the open hearth buildings did not anticipate the installation of any equipment on the roof. The reasons for moving the unit off the charging floor were to avoid vibration

*Presented at the Semi-Annual Technical Conference of the Air Pollution Control Association held at Houston, Texas, The Rice Hotel, Dec. 3-5, 1956.

Fig. 2. Installation of precipitators on roof area.

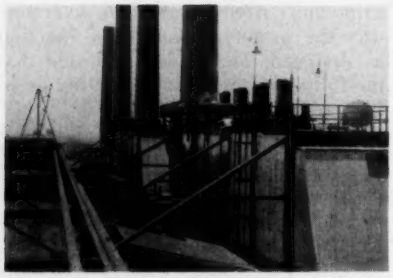

Fig. 3. Roof design minimizing vibration from other operations.

Fig. 4. Appearance of installation at early stage.

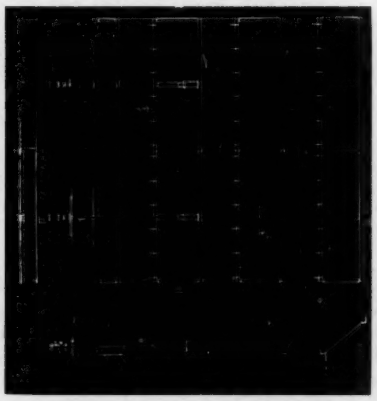

Fig. 5. (Above) Additional considerations in design to strengthen collection electrodes for heavy rapping.

Fig. 6. (Right) Perforated baskets to minimize turbulent flow of entering gases.

within the unit, to isolate the installation, to provide more adequate servicing and maintenance, and also to obtain sufficient height for removing dust collected in the unit. The problem of mounting the precipitator on the open hearth roof became one of developing a design so the unit would not shake or vibrate with the passage or movement of cranes, charging machines, or other equipment in the open hearth shop (Fig. 3).

Description of Precipitator

As installed, the precipitator resembles a rectangular duct with a width of 17 ft. 8 in., an overall length of 59 ft. 8 in. from gas inlet to gas outlet, (Fig. 4) and a height from the dust outlet hopper to the top of the high voltage terminal housings of 43 ft. — 0 ft. 4 in.

It is designed to handle 58500 cfm. of dust-laden gases at 460 to 470° F. and 29.92 in. Hg. The moisture content of the gases entering the precipitator ranges between 8 to 12% H_2O by volume. The average inlet loading is 0.43 gr./ft.^{3} at normal operating conditions. The pressure drop or draft loss permitted between the inlet and outlet is 0.5 in. of water. The structural steel support of the precipitator is designed to be integral with the precipitator shell structure.

Strengthening and reinforcing of the precipitator was necessary since it had been determined from previous tests and operating data that commercial precipitators, as presently manufactured, are too light in design for the extremely heavy duty required in open hearth service.

Precipitator reinforcing is important because vibration or movement within the precipitator must be kept to a minimum since this vibration, or shaking of the discharge or collecting electrical sections, would cause arcing and shorting of the electrical system.

The discharge and collection electrode systems were strengthened to risist the rapping cycles which are considerably heavier than currently practiced in conventional precipitator design (Fig. 5).

Dust hoppers were provided with round corners, and the openings at the bottom of the hoppers were enlarged to permit freedom of movement of the dust. When square corners or shelves were found to cause dust build-up, they were removed by placing a round steeple over them.

In our early studies we determined that the flow of gas entering the precipitator is very important as well as its distribution within the precipitator proper, for maintaining maximum efficiency at all times. This distribution section ahead of the electrostatic field was provided for the following 3 reasons:

1. To give the gas an opportunity to slow down and to reduce turbulence as much as possible.
2. To check out the heavy particles of material in the gas stream caused by blowing checkers or boiler tubes.
3. To provide space in the event it became necessary to add additional electrostatic fields to the precipitator for obtaining a higher collection efficiency than is possible with the present unit.

The entry of the gas into this first section was through a specially designed duct with baffles in it in such a manner that it would reduce turbulence to a minimum, and cause the gas to flow over

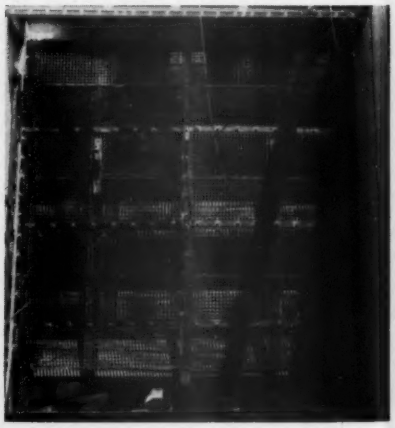

Fig. 7. Flat perforated plate installed on outlet side.

the entire area of the entering section of the precipitator. At the end of this section, and just ahead of the electrostatic field, a distribution plate was placed consisting of 3 curved, perforated baskets extending across the width of the precipitator (Fig 6). These baskets are mounted in such a manner as to provide uniform flow through the electrostatic field. This innovation was reached after several months of study with a water model and is one of the major contributions to this science. The design of gas distribution equipment within the precipitator proper also included baffles placed between the electrostatic fields and at the bottom of these fields. The baffles keep the gas from short-circuiting down into the hoppers and also maintain a relatively uniform flow through the grid work of the electrostatic fields.

At the outlet end of the precipitator, an additional flat, perforated plate was installed to keep the gas from short-circuiting to the outlet duct (Fig. 7).

Several designs were studied in the outlet duct, but the one appears to be the most practical and is being improved in current installations.

From an operating point of view, there are advantages still to be gained if a little additional straight duct section could be added to the outlet.

To keep the distribution equipment clean, soot blowers were provided to clean the openings in the perforated baskets and to remove any dust build-up in the outlet duct. These distribution systems have also been equipped with rappers (Fig. 8).

The residence time of the gas in the electrostatic field is related directly to distribution and overall precipitator efficiency. It has been found that effective collection at temperatures indicated may be obtained with a gas flow of approximately 2 fps. Four to 6 fps. is considered too high and re-entrainment of the collected dust at this velocity reduces the efficiency.

Conditions in the precipitator change rapidly, such as encountered during a lime boil when the fume changes from a metallurgical type to an alkali type. Also, during a hot metal charge, the concentration of metallurgical fume increases greatly.

Variable operating conditions of this magnitude and frequency present unusual precipitator power control problems.

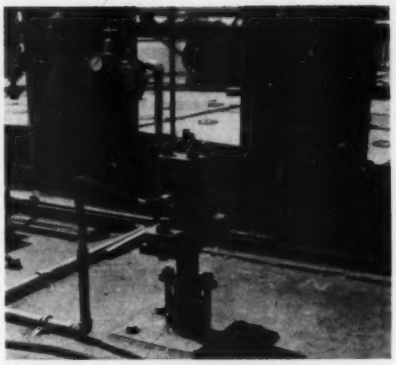

Fig. 8. Equipment provided to keep perforated baskets and ducts free of dust build-up.

Tests have been conducted with resistance control and monocyclic constant current network control in addition to the saturable reactor control installed on No. 9 precipitator. Although not fully conclusive, these tests indicate that saturable reactor control with added control circuit inductance is probably most satisfactory for this service.

Automatic feed back connections to maintain voltage near the *sparkling* point in the precipitator will undoubtedly improve precipitator performance.

The No. 3 precipitator had the conventional mechanical rectifier equipment. No. 9 precipitator was designed to employ saturable reactor control with selenium rectifier transformers. While the first cost of selenium rectifiers is higher than that of mechanical rectifiers, it has inherent operating advantages. It maintains a higher RMS voltage in the precipitator permitting improved precipitator operation.

The sequence and type of rapping is important for best precipitator performance. The unit was originally equipped for external rapping of the collecting curtains. The rapping for the discharge electrode system was within the precipitator and was connected to the external air service through stainless steel tubing. The 2 systems were originally scheduled to operate automatically on 1 hr. 30 min. intervals. We have learned that under certain conditions, the fume has a tendency to be sticky in nature causing build-up on the discharge electrode frame work and on the collection frame work as well. Sometimes the dust, as collected, would sinter and no amount of rapping would remove it. In No. 9 precipitator, the discharge electrode frame was designed to be one complete self-supporting and rigid unit.

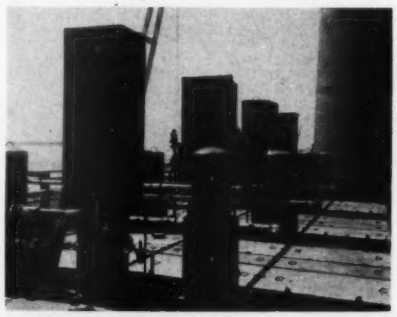

Fig. 9. Outside wrappers for discharge electrode frame.

The rapping of this equipment was handled through outside rappers mounted on insulators which, in turn, are mounted in an air-cooled chamber (Fig. 9). This has eliminated the problems of build-up, and keeps the precipitator relatively clean which will reduce corrosion and improve precipitator performance.

The collecting curtain system is similarly supported. The rapping cycles have been cut to 30 or 40 min., and when extremely dirty material has been charged to the furnace, it may be manually rapped from the operating floor of the open hearth. It is essential that the dust removal from collecting and discharge electrodes be accomplished as quickly as possible after it has built up and the time limits indicated appear to be the most effective. In connection with rapping, the low gas flow rate previously mentioned becomes important.

The rapping is a sharp, hard blow of substantial intensity and each blow is perhaps 2 sec. apart. This is a much better type of rapping for open hearth fume rather than a series of short frequency blows because the latter tends to pack the dust upon the collecting curtain.

A problem of condensation within the precipitator proper was corrected by the installation of light-weight insulating aggregate concrete on the roof of the precipitator with a ferrule embedded around its perimeter. The insulation on the precipitator proper was a blanket-type material covered with an aluminum sheet properly flashed to the ferrule reglet on the roof perimeter. The hoppers, since they extend below the roof line, were not insulated and the dust within them provides this insulation.

The control house for the precipitator is of corrugated aluminum construction provided with air cooling, and is as close to the precipitator unit as possible, to reduce line losses and corrosion of bus duct (Fig. 10).

Fig. 10. Control house location in relation to precipitator.

The inlet and outlet duct to the precipitator is equipped with expansion joints of the spun bronze type, otherwise the unit is as completely rigid as possible.

Installing the precipitator outside in this fashion also eliminates the installation of concrete control houses and transformer houses, since with an outdoor installation it is possible to use a tray on which the transformers may be mounted (Fig 11). All hatches in and around the precipitator proper have been designed for easy access.

The precipitators include automatic rapper controls and mechanical devices to reduce operating attention and maintenance to a minimum.

Also, remote meters are placed in open hearth control centers so that the precipitator operating conditions may be watched by operators without going to the precipitator control house.

However, in order to maintain the precipitator at peak performance at all times, some preventive maintenance and operating attention is required.

Records of primary volts and amperes, and of secondary milliamperes provide a permanent log of precipitator operation. Records of this type are very important in comparing day to day operation and also long period operating trends.

The precipitator control house is located on the open hearth building roof, a location that is rather hot and dusty at times. Effective air ventilation and cooling system operation in the control house is very important to prevent deterioration of electrical control equipment, such as timers, relays, and contractors.

Insulators on the precipitator, in the control house and in bus ducts may be broken or damaged by flash-over if they have a coating of conductive or

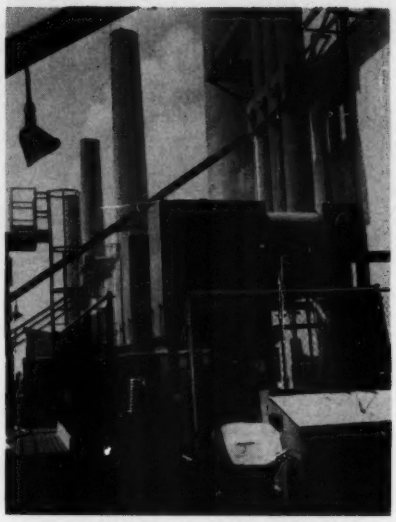

Fig. 11. Installation of transformers.

semi-conductive dust. A ventilating system for the precipitator insulator compartments is provided to protect the insulators. Periodic inspection and cleaning of all insulators is recommended to make certain that vent systems and housings are effective.

Rapping system components, including pneumatic rappers, solenoid valves, air cleaners and piping connections are inspected and adjusted at regular inter-

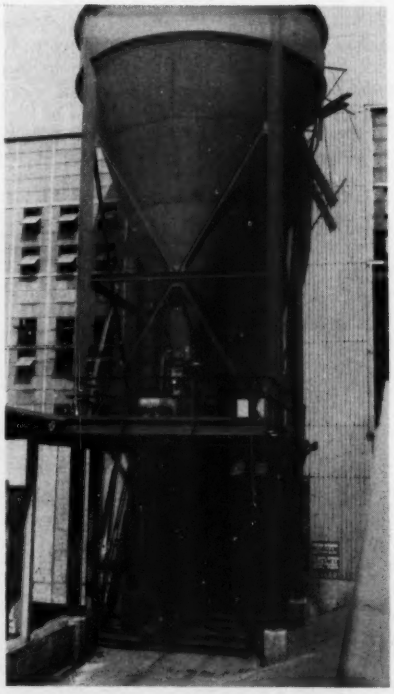

Fig. 13. Dust storage bin.

Fig. 12. Precipitator hoppers and dust removal system.

vals. All of this equipment is located for easy access to facilitate inspection and maintenance.

Electrode alignment is extremely important as one point of minimum electrical clearance in a precipitator will limit the maximum voltage that can be applied. Hence, electrode alignment and electrical clearances should be checked at intervals when furnaces are down for furnace or boiler repairs or maintenance. These checks, together with careful inspection of electrodes and supports should obviate any loss of time due to precipitator repairs or reduction in efficiency due to internal difficulties.

The dust removal system consists of motor operated rotary feeder valves on each precipitator hopper which discharge to screw conveyors (Fig. 12).

The conveyors deliver the dust to a Fuller-Kenyon pump, and it is then pumped to a 25 ft. diam. storage bin located outside the open hearth shop building (Fig 13).

The collected dust flows freely when it is hot and aerated, but it is much more difficult to handle when cold and de-aerated. Thus it is important that the dust is not stored in the precipitator hoppers for hours, but removed frequently in order to facilitate removal and handling.

After a unit has been installed, and prior to its acceptance, certain tests are required. The Kaiser Steel Corporation has developed methods and procedures as well as equipment that are now considered by the industry as an important step to more accurate results. It is possible that some of these will become accepted standards soon.

The final and most important check on precipitator performance is given by actual efficiency and stack emission tests at regular intervals. Operating and maintenance techniques, developed by Kaiser Steel during the years since Pre-

Fig. 14. Stack with precipitator off—165 lbs. dust/hr.

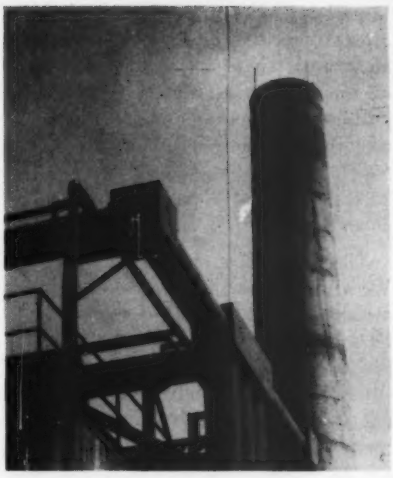

Fig. 15. Stack with precipitator on—12 lbs. dust/hr.

cipitator No. 3 was installed, have reduced stack emission and boosted precipitator efficiency as compared to data obtained during acceptance tests conducted soon after installation was completed.

The precipitators at Fontana are now operating with an outlet grain loading in the neighborhood of .025 gr./ft^3 and actually emitting to the atmosphere between 6 and 11 lbs. of particulate matter/hr. (Fig. 15). The average amount of particulate matter entering the precipitator is about 160 lbs./hr. (Fig 14).

Some of the key points that have been outlined here in the design of open hearth No. 9 precipitator are being carried forward in the current installation of precipitators 4 and 5. The contribution made with this installation consists of basic data of value to the trade as a whole. The use of selenium rectifiers rather than mechanical rectifiers, special collecting and discharge electrodes; special design and application of rapping mechanisms; and the development of gas distribution apparatus are among the most important.

Electrostatic precipitators for use on open hearth furnaces should not be purchased on price alone. Many of the hidden values indicated here are not on the average price tag, and will spell the difference between poor performance and good operation, low maintenance and long life.

The Control of Effluents from Municipal Incinerators*

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As our cities become larger and more densely populated, refuse disposal grows both as a technical and an economic problem. Sanitary fills which were once popular have become expensive because of the higher cost of land as well as the longer distances for hauling which are necessitated by the increase in the size of the cities. Labor costs have made garbage reduction after sorting an almost profitless enterprise, and very few cities are using this method at the present time. Health authorities have frowned on hog feeding as a means of garbage disposal; in fact, the hog feeders themselves have found this method to be impractical and dangerous. An increase in the desire to control air pollution has just about ruled out the old idea of open-dump burning for trash. Whether garbage is segregated at the source for disposal in individual or municipal grinders or whether garbage and combustible trash are combined, incineration is the only feasible means by which to dispose of the combustible materials.

Although incineration has for ages been a welcome and convenient means for waste disposal, we have all been aware at times of the smoke and fly-ash nuisance which it creates. Recent studies[1] have shown that a typical backyard incinerator emits as much as 3 lbs. of aldehydes for each 100 lbs. of household refuse handled, and appreciable quantities of methanol, ethylene, phenols and other organic materials. Most of the separately fired residential incinerators probably do much better than this. However, there is still need for continued research and testing so that improved designs can be developed and sensible restriction enforced.

Even though the household and apartment-type incinerators are improved and installed in greater number, there will still be need for municipal incineration in the larger cities. Most large cities such as New York and Chicago have been using incineration as a waste-disposal method for years and are now expanding their facilities. Westergaard[2] has pointed out that the present incinerator expansion program in the city of New York will cost approximately $70,000,000 and result in the construction of 10 new units as well as the rehabilitation of 5 existing ones. Los Angeles has waited much longer than most cities to convert from individual backyard to municipal incineration but has begun to do so as a means of minimizing air pollution.

In the field of municipal incineration

* Presented at the East Central Section Meeting of the Air Pollution Control Association, September 17, 1956, at Columbus, Ohio.

[1] J. E. Yocom, G. M. Hein, and H. W. Nelson, A Study of Effluents from Backyard Incinerators. *J. Air Poll. Control Assoc.* 6, 84-9 (August 1956).

[2] Vigo Westergaard. Traveling Grates Find a New Field of Usefulness. *Combustion* 40-5 (June 1956).

there is still a great need for basic operational data from the many present installations. There are units which, from an incineration as well as from an air-pollution viewpoint, are doing an exceptionally fine job; there are others which are neither good incinerators nor acceptable insofar as air pollution is concerned.

The overriding factor is economic. We already know how to devise reliable systems which will effectively and unobjectionably reduce municipal garbage and trash to ash which can be useful as fill material. But their first and operating costs may sum up to more than many municipalities are willing to pay for the result. Mechanical feeding and firing, overfire air jets and, if necessary, high efficiency collectors can be combined in amply sized systems to convert almost all the refuse to carbon dioxide and water vapor without objectionable fly ash or odor. Much research is needed to attain these results with lower costs.

So long as the landfill means of disposal was generally economically more attractive, there was no incentive to develop incineration. Now that an increasing number of cities are facing rising costs of landfill areas and of haulage, greater attention must be paid to reducing the costs of acceptable incineration systems.

Rogus[3] also reports that New York City will turn increasingly to incineration in the years to come. Even though landfill has been cheaper, sites are becoming fewer, and improved design promises to make incineration economically even more attractive. In 1953, Rogus reports that landfill cost was $2.26/ton while the average incineration cost of 12 plants was $4.78. However, the new Gansevoort Incinerator has averaged only $2.50/ton. A new plant at Rochester, New York, is reported[4] to have a basic operating cost of only $2.39/ton including the cost of operating a stack-gas washer. The initial cost of the plant was $1,373,726. Hence, it appears that incinerator operating costs are becoming competitive with landfill costs and the principal remaining problem is to assure their clean operation.

[3] Casimir A. Rogus. Sanitary Fills and Incinerators. *Am. City* 114-115 (March 1955).

[4] John V. Lewis and Newell L. Nussbaumer. Two New Incinerators. *Am. City* 105-108 (September 1956).

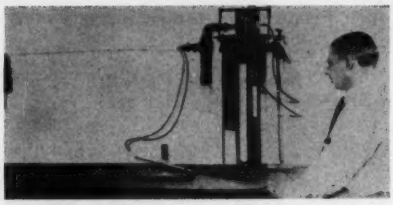

Fig. 1. Dust-sampling equipment showing probe and Pitot tube, primary collector, secondary collector, venturi ejectors, and instrumentation.

Dust-Emission Measurements

Battelle has been interested in air-pollution control for many years and has been actively engaged in research work with municipal and domestic incineration for the past 5 years. Prior to the actual field testing of incinerators, considerable work had been done on the measuring of fly-ash emission from coal-fired boilers. During this previous work, we developed a large-volume gas sampler as well as a technique which gave reproducible results in measuring dust emission[5].

Fig. 1 shows this sampler which, with very little modification, was used for our incinerator test work. A pitot tube, attached to the sampling probe, measures the velocity of the flue gases at the point of sampling. The rate at which the gases are exhausted through the nozzle is regulated to assure isokinetic sampling. When air of sufficient pressure is available, the aspirator is used for exhausting the gases; when the air is not available, an exhaust blower is used. The gases were filtered by a double orlon bag which proved to be 97.4% efficient for material in the size range of 0 to 7μ. For some of the test work, the tube is used upstream of the filters; at other times a secondary filter of fiber glass is used following the filter bag. This secondary filter is considered to be *absolute*. A thermocouple is attached to the sampling nozzle so that the fluctuations in gas temperature can be noted and the proper adjustments made.

Incineration is far from a steady-state process and thus presents a problem insofar as accurate ampling is concerned. During all our previous test work, the furnaces were fired at as constant a level as was possible. For incinerators, the actual test time was extended to a 4 or 5 hr. period so as to permit the use of as many points as possible. By sampling for 10 min. at each point, it was believed that a sufficiently representative sample could be obtained even though there were measurable fluctuations. If the gas flow varied beyond just a momentary fluctuation, the difference was noted and the sampling rate changed.

Samples of the flue gas were taken from various points in the system as well as at the point of actual sampling. This is necessary if any adjustment for excess air is to be made. Also, it permits the proper evaluation of the entire system insofar as velocities and leakages are concerned.

Other methods of sampling have been used and no doubt have their merit. The Los Angeles County Air Pollution Control District uses the wet-impinger method followed by a dry thimble. This assures the collection of soluble salts which may have been vaporized by the high temperatures of the furnace, and provides an efficient filtering method for the collection of the very small particles. There are others who prefer to use a thimble directly in the sampling nozzle. Although we are always seeking new and improved methods, we have not as yet found it necessary or desirable to change appreciably from our present

[5] W. C. Holton and E. J. Schultz. Some Notes on Dust Sampling Equipment and Technique. *Trans. ASME*, 1327-32 (1953).

TABLE I

Measured Emissions from Municipal Incinerators Without Auxiliary Dust Collection

Unit	Fly-Ash Emission, lb./1000 lb. gas at 50% excess air		Fly-Ash Emission, lb./ton of refuse
	Range	Average	
Milwaukee Units[6]	1.30-3.00	2.70	10.0-26.0
Pomona Fair Grounds[7]	0.82-0.99	-(a)	-(a)

(a) Not reported.

[6] F. R. Rehm. Incinerator Testing and Test Results, Paper 56-6 presented at 49th Annual Meeting of APCA, Buffalo, N. Y., May 20-4, 1956.

[7] C. B. Afflerbaugh. It's O.K. in Los Angeles. *Am. City* 72-74 (December 1955).

method which provides for the collection of a sample of substantially larger quantity than other methods.

Typical Fly-Ash Emissions

Although there is still a great need for additional data, the results of some studies already completed by others show both a surprising similarity as well as a definite need for an improvement in most of the present incinerator dust-collection systems.

Table I shows the tabulated results of some published test work. Additional incomplete and unpublished data on other large incinerators indicates emission rates of lb./1000 of gas and lb./ton of charge in the same range as Table I.

It is apparent that the settling-type of collection system usually incorporated into the design of these larger units either needs improvement or else additional collection equipment must be added. The average dust emission, corrected to the standard of 50% excess air, is well above the standard of 0.85 lb. set by the ASME code. It should be noted that even with the high rate of fly-ash emission, only about 0.5 to 1.5% of the initial charge is emitted as fly-ash. This compares with a typical emission of about 5% of the total amount of fuel fired in pulverized coal or spreader-stoker-fired units when operating without dust collectors. True, there is a difference in the principles of combustion; the coal-fired furnace is designed primarily for suspension burning whereas the incineration process is usually designed for burning on the grate. Also, the boiler must aim primarily at recovering useful heat, not wasting it. But such data would indicate that the best incinerators cannot greatly reduce ash entrainment and that the main efforts must be concentrated on the collection of the entrained fly ash rather than the improvement of the combustion itself. Of course, many other present incinerators are not designed to minimize entrainment and so could be improved in that regard.

Alternate Methods of Collection

For a long time, the settling chamber was the only type of collection system considered for larger incinerators. Because it can be built of refractory, the high flue-gas temperatures are not a serious problem and no costly heat-exchange equipment is necessary. Velocities in the range of 4 to 8 ft./sec. have been widely accepted as giving satisfactory dust settling, and vertical deflecting baffles have been used to create some turbulence in the hopes of improving the collection.

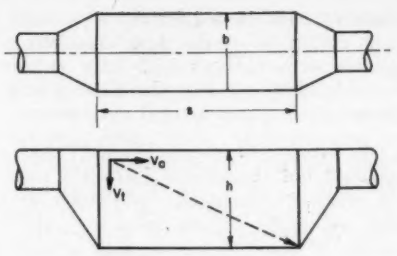

Fig. 2. Sketch of sample settling chamber.

Fig. 2 shows a sketch of a simple settling chamber. If the horizontal velocity of the particle, which is determined by the velocity of the flue gas, is reduced enough, the free-falling velocity of the particle will permit the entrained dust to settle to a quiescent zone near the bottom of the chamber. Theoretical calculations show that to collect particles even as large as 44μ, the gas velocity would have to be reduced to 1 ft./sec. for a chamber which has a ratio of length to height of about 4 to 1. The cross-sectional area needed for such a low gas velocity makes this impractical for most installations. Even with flue-gas velocities of about 4 ft./sec., which are often considered to be excellent, the ratio of length to height would have to be about 17 to 1 in order to collect the 44-μ particles. Because typical analyses indicate that over 30% of the fly ash being emitted is smaller than 44μ it is apparent that something better than the simple settling chamber is needed if the present ASME code is to be met by incinerators.

There are installations which have made use of mechanical collectors. The maximum gas temperature which can be tolerated by the ordinary metallic cyclone-type mechanical collectors is in the range of 500 to 600° F. This means that the gases from the incinerator, which normally run from 1200 to 1800°F., must be cooled by a heat exchanger, by dilution with cooler gases, or by water sprays. All these cooling methods are expensive and costly to maintain. Unless an incineration plant can be used in conjunction with a steam-generating operation, mechanical collectors do not appear to be practical for the average installation.

Wet scrubbers, such as are used in many chemical processes, will do an excellent job of removing the fly ash. The 2 big drawbacks are the high initial cost and the water-supply and disposal problem. A high-efficiency scrubber which has sufficient capacity to handle the large volumes of gas from an incinerator without an excessive pressure drop, is likely to cost more than appears to be justified for the fly-ash-removal portion of the installation. Simpler moderate-efficiency sprays have been claimed to be satisfactory where water disposal is no problem. Even when the water is recirculated, an ample settling system is required. It may be that as the areas around the incinerators become more heavily populated and the controls become more strict, further consideration will have to be given to the use of high-efficiency scrubbers. As it is, very few are being used at present.

If electrical precipitators are not considered because of the high temperatures and high cost, we are left with the possibility of using some type of simple inertial collector, wet or dry, which can be constructed with refractory, or heat-resisting materials.

An inertial type of separator depends upon a sudden change in the direction of the gas flow to separate the particles of dust from the conveying gas. Some type of baffling is needed not only for the changing in direction of the gas flow but also for the providing of quiescent zones in which the separated particles can settle. Some of the baffling done in the settling chambers at the present time is a step in this direction. However, more drastic changes in design are needed if the maximum efficiency of the chamber is to be realized.

Incomplete experimental work on baffling indicates that it may be possible to more than double the collection efficiency of a simple dry settling chamber. When water is used, either in the form of sprays or as a settling basin on the floor of the chamber, it appears that further improvement can be obtained. The municipal incinerator at Milwaukee, Wisconsin, has been reported to use a water pond in the breeching which has reduced the fly-ash emission to below the maximum allowable level of 0.85 lb./1000 lb. of flue gas, adjusted to 50% excess air[8]. It would appear that such improvements, if verified, could be applied simply to many existing plants. However, once a settling chamber has been built there is often little that can be done to improve it because of the high cost of changes of refractory structures. Hence, development work must be done by means of

[8]W. M. Swietlik, Water Sprays Give Milwaukee a Fly-Ash Free Incinerator. *Am. City* 90-2 (September 1954).

models, with the results being verified by field measurements.

In any event, it is becoming clear that simple settling chambers will not do an acceptable job in recovering the fly ash from the flue gas. Rehm[6] has concluded that the use of dry fly-ash collection devices such as checkerwork and refractory drop curtains will probably not reduce the emission to an acceptable level. The use of baffles and checkerwork patterns in a certain incinerator which was being tested, resulted in a fly-ash emission ranging from 1.20 to 1.40 lb. dust/1000 lb. of gas, adjusted to 50% excess air.

Conclusions

Incinerator designers should recognize that even the *ideal* settling-chamber velocity of 4 ft./sec. will permit little settling in the majority of cases. If simple inertia-type collectors cannot be built to provide satisfactory separation and collection of the dust, then water sprays or scrubbers will have to be considered along with the more costly installation of mechanical collectors.

As Greeley, Clarke, and Gould[9] have pointed out, additional full-scale tests of existing installations are needed. To this we would add the need for publication of more complete data already accumulated by the air-pollution control offices of various cities where outstanding installations have been made. It would be particularly helpful if a detailed comparison could be made of the most modern installations to indicate what effect the type of furnace, ratio of under- to over-fire air, and rate of burning had upon fly-ash emission. Also, true cost comparisons are much needed. More data are also desirable for the important task of determining what might be considered a fair and just air-pollution code for the incineration process.

Incineration as a means of refuse disposal is here to stay; in fact, it is increasing rapidly. No longer can either industry or municipality afford simply to build any type of incinerator just so long as it burns most of the charge. Air pollution from municipal incinerators must be much less than it has been in the past. It is time that municipal incinerator designers become realistic in the establishment of specifications for collection chambers. The simple, massive settling chamber was attractive because it required little maintenance, but it is no longer good enough for today's demands for cleaner air.

[9] Samuel A. Greeley, Samuel M. Clark, and Richard H. Gold. Incinerator Design and the Fly-Ash Problem. (Part III, Conclusion) *Am. City* p. 169 (July 1955).

A Summary of the Fly-Ash Disposal Problem*

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The problem of fly ash collection and disposal has gradually become an interest of major importance to most large coal burning companies using pulverized firing.

Bituminous Coal Research, Inc. has watched this trend and has been actively engaged in a program involving fly ash utilization in established outlets and investigating possible new markets.

Increased coal usage has magnified this problem particularly because most of this increase is pulverized firing. As long as the fine ash could be blown out the stacks the producer had little or no problem.

The program on air pollution has now changed much of this condition and many areas have ordinances requiring collection of this ash. Disposal of this ash is expensive and getting more so. Disposal areas are becoming a problem.

Utilization in established outlets or processing have accordingly assumed greater importance.

The size of this problem can be realized by looking at some of the survey results. Mr. Weinheimer of the Detroit Edison Co. published figures several years ago which gave fly ash production for the years 1943, 1953 and 1963. There were 2.8 million tons in 1943, 6.8 million tons in 1953 and 13.7 million tons by 1963 and this might go as high as 16.8 million tons/yr.

We have compiled a recent country wide inventory of fly ash and this figure will show how we are progressing in respect to production since the 1953 date.

1943	*1953*	*1956*
2.8 million	*6.8 million*	*8.25 million*

Our figures show it is not uncommon for a utility system to have as much as a million tons/yr. of fly ash.

Outlets for amounts of this material must be large in order to keep up with production rates.

Established Outlets

Over the years, a number of uses have been developed and significant amounts of fly ash are being sold in some of these outlets. This list is as follows:

- Ready mixed concrete
- Building blocks—cinder and concrete
- Slag and clay bricks—ceramic shapes
- Stabilized soil composition and lime-fly ash mixes
- Bituminous mix fillers
- Road base choking material for highway construction
- Lightweight aggregate manufacture by sintering or cyclone furnace
- Metal polishing agent and mild abrasive
- Sand substitute in sand blasting
- Filtering medium
- Soil conditioning agent
- Filler material in roofing and putty . . .

The subject of specification is very important. The composition of fly ash determines whether it can be used in certain applications.

*Presented at the East Central Section Meeting of the Air Pollution Control Association, September 17, 1956, at Columbus, Ohio.

Large amounts of fly ash have been used in concrete and from these uses have come definite specifications. Probably the most important of these is the ASTM specification. There are also 7 other specifications in existence for fly ash essentially the same as this but with individual modification depending upon the area in which they were developed.

ASTM Designation C 350-54T

Chemical Requirements

SiO_2 — 40.0%
MgO — 3.0% max.
SO_3 — 3.0% max.
Moisture 3% max.
Loss on Ignition — 12.0% max.
Available Alkalies as Na_2O—1.5 max%

Physical Requirements

Fineness—SP. Surface by air permeability test sq. cm/gm of material minimum — 2800
Compressive Strength —
100% of control at 7 days
100% of control at 28 days
Drying Shrinkage — .1% max. 28 days
Air-entraining admixture in concrete
Soundness — refers to autoclave expansion of mortar cubes — max. 50%
Uniformity Requirements — very detailed in explanation form.

You will note this specification makes no mention of iron oxide or aluminum oxide. Many other specifications have limits for aluminum oxide but none to my knowledge makes any mention of iron oxide content. . . .

Possible New Uses

New large volume outlets are needed for fly ash in order to relieve the disposal problem. Some of this material is being shipped long distances, but this is not economical in most cases. This material must be used in the production area where hauling distances are not great. This condition almost certainly means that new processes must be developed to use fly ash or that the material be modified or adapted as a raw material for some existing production operations.

As of the present, there are no large scale new processes to report. We look at existing possibilities as far as processing is concerned. In addition to the sintering of fly ash to make lightweight aggregate, we think there is some merit to the use of this material to make glass. We have been trying to work out the requirements for this use. The iron oxide content must be removed to a very high degree and the fly ash might need to be agglomerated to fit properly in the glass making furnace operations. Obviously, this is not easy or it would have been done before now. The glass industry is a large market.

Another idea we have been investigating is the possibility of making cement itself from fly ash. We will need to find out much more than we know now; however, we think this idea is worth considerable time and effort.

Conclusion

We believe fly ash can become a valuable raw material and that its sale price can equal that of the original coal. This condition would be a definite financial advantage for large coal burners who could treat this as a fuel discount. One point usually overlooked in this fly ash picture is the one of coal burning efficiency. Many times the coal consumer, because of his interest in selling his fly ash first finds out that his burning performance is not what it might be. Heretofore, high carbon percentages in fly ash have gone unnoticed. This condition reduces the acceptability of the fly ash as a commercial material.

The important point is this. When a large pulverized coal burner makes a serious effort to improve his fly ash carban content, he may save himself several tons of coal a day and maybe more. If he never sells a pound of fly ash he has improved his burning practice and saved himself many dollars day after day by getting usable heat from the carbon content which previously went out the stack unburned.

Fly ash is rapidly being recognized as a process material and large scale projects are using more of this material for quality and economic advantages. This practice will need to be continued and expanded. There are still many potential outlets where fly ash could be used and a thorough merchandising job must be done as with any other product. Most of this work is the responsibility of the supplier. Our organization is trying to assist in this marketing work. We make our test results generally available to prospective users. We keep a complete record of developments in this field and we try to develop new applications.

Dustfall Measurements*

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In surveys of urban environmental conditions, efforts are frequently made to measure dustfall. Equipment for this purpose usually consists of a simple bowl or basin into which dust particles, rain, snow, *etc.* may drop. In some instances the collecting basin is the receptacle to hold the settled material for the interval under study, usually for a period of 1 month. In other instances, the receptacle drains into a bottle or other container which is removed once monthly. The choice of a collecting bowl appears to be related to materials available, prior use in the area being surveyed, precedent established by usage in other localities concerning which dustfall data have been published, or the adoption of modified types of equipment believed to constitute improvement over older types or to have unique value in the survey being undertaken. Although the selection of type of settlement basin may be made very wisely for the immediate needs, the fact that there is no internationally accepted design makes difficult, if not impossible, the comparison of dustfall conditions in various cities. In an endeavor to illustrate this difficulty and also to provide data which might be used to permit a measure of comparison between published reports, experiments have been conducted using various dustfall basins. The basins used

*Presented at the American Chemical Society Symposium on Air Pollution, at Atlantic City, N. J., Sept. 16-21, 1957.

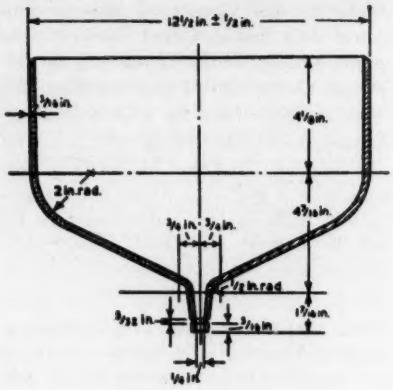

FIG. 1
Collecting Bowl
British Standard

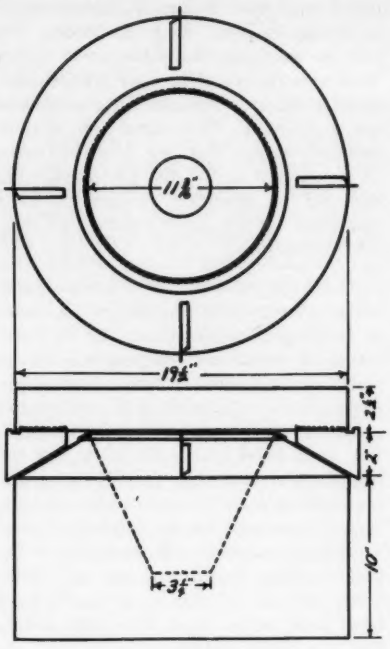

FIG. 2
Collecting Bowl
Detroit and International
Joint Commission

FIG. 3
Collecting Bowl
Pittsburgh Study

have been the British Standard [1], the type used in Detroit and by the International Joint Commission kindly loaned by Mr. B. C. Newbury of the Ontario Research Foundation, Toronto, the Pittsburgh equipment as proposed for consideration by the Technical Coordinating Committee of the Air Pollution Control Association [2] and a basin such as has been used in various surveys in Toronto since 1932. The dimensions of each of these 4 pieces of equipment are shown in Fig. 1, 2, 3 and 4 respectively. The records presented herein are dustfall records taken with these pieces of equipment at an elevation of 3.8 ft. above the roof-level of the School of Hygiene Building, University of Toronto. The roof of this four-story building is about 51 ft. above ground level.

Duplicate Determination

In the use of any piece of equipment it is desirable to have knowledge of the accuracy of the results. With dustfall studies it is difficult to make *control* exposures but it is possible to expose 2 identical basins simultaneously at one site and thereby obtain information concerning the variation which may be expected. Table I is a record of dustfall as measured in 2 basins of the Toronto type over several months. It will be noticed later that the differences between the values found in this comparison are about ±5% and, as is shown later, are much smaller than the differences found when similar experiments are conducted using certain pieces of equipment of differing types.

The errors which may be involved when making comparisons of dustfall records without a knowledge of the type of equipment used to collect the dust is clearly illustrated in Table II showing a record of collections with equipment in use in the Detroit River area by the International Joint Commission, and with equipment of the Toronto design.

Having in mind the large number of measurements made in the United Kingdom over many years, determinations have been made with the British Standard Bowl. Determinations have also been made with the bowl proposed for consideration by a committee of the Air Pollution Control Association of the type shown in Fig. 4 and such as has been in use in Pittsburgh. Dustfall measurements made at one location with these 2 bowls and with the 2 bowls previously discussed are recorded in Table III.

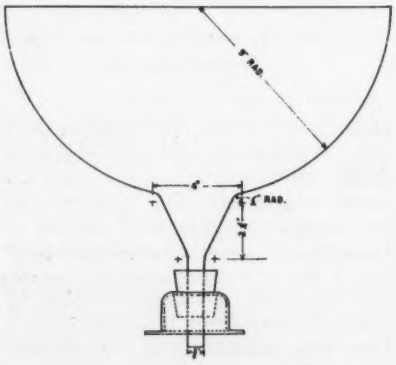

FIG. 4
Collecting Bowl
Toronto Study

From the results shown in Table III it is clear that mere reference to tables of dustfall cannot provide an estimate of relative dustfall in various locations unless there is a knowledge of the type of gauge which is used and some approximation is made in the light of differences in equipment. Present indications are, firstly, that the British Standard Gauge and the Toronto Gauge provide approximately equivalent results; secondly that the results recorded by the Detroit International Joint Commission type are approximately 185% of those recorded by the British Standard or Toronto type; and thirdly, that the results recorded by the Pittsburgh type proposed for consideration by APCA are approximately 150% of those recorded by the British Standard or Toronto type. Obviously a precise comparison between the various gauges

(1) Deposit Gauges for Atmospheric Pollution, British Standards Institution, B.S. 1747 (1951) London.

(2) *J. Air Poll. Control Assoc.* 5, 176 (1955).

TABLE I

Dustfall Gauge—Toronto Type

Dustfall in Tons (2000 lbs.)/sq. mile/month as measured by 2 adjacent gauges

1953

Gauge	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1	36.6	28.7	37.9	26.0	—	24.4	18.2	—	24.2	28.4
31	38.2	30.3	37.2	25.1	—	25.0	18.4	—	23.1	28.6
Difference	—1.6	—1.6	0.7	0.9	—	—0.6	—0.2	—	1.1	—0.2

1954

Gauge	July	Aug.	Sept.	Oct.
1	12.6	20.8	22.8	31.4
31	14.6	20.9	22.0	30.0
Difference	—2.0	—0.1	0.8	1.4

must await the collection of further data.

It would be of value to determine the reason for the conflicting results given by various dustfall gauges. It might be thought that dust settles in a gauge only to be blown out by a subsequent breeze. If this is so, it is clear from the results recorded in Table I that, in the case of the Toronto gauges, and by inference the British Standard, the amount blown out of one gauge is very close to that blown out of another. However, it was thought that some information on the matter of wind removal of settled dust might be obtained from data provided by 2 gauges of one type, one gauge being washed at regular intervals to transfer the settled dust to the collecting receptacle beneath the basin. Two gauges of the Toronto type were therefore established at one site. In one of the gauges the settled dust was washed into the collecting receptacle by rainfall and by washing at the end of the month. The other gauge was washed 3 times weekly with distilled water to transfer the dust to the collecting receptacle. The results are shown in Table IV.

From the results shown in Table IV, it is evident that some settled dust may have been removed from the dry gauge, possibly by wind, but the quantity removed does not appear to be sufficient to explain the differences shown between gauges of various types. In the case of the Pittsburgh gauge it is unlikely that any dust was removed by wind since the gauge always contained water.

An explanation for the difference between data from gauges of various types has been sought in an examination of the absolute and relative amounts of soluble and insoluble solids in these gauges. No acceptable explanations for the differences have been forthcoming.

Summary and Conclusions

Sensenbough and Hemeon[3] have discussed a number of variables in dustfall measurements. They have shown that values obtained from identical gauges at one location may commonly have errors of 10 to 15%. The data presented herein for gauges of one type are within these limits but show that the values obtained with gauges of some types may differ by as much as from 50 to 100% from values obtained by gauges of another type. Such variations make it difficult to effect comparisons of dustfall between cities and to judge relative efficiency of various measures directed to the improvement of atmospheric conditions. It is hoped that the adoption of a simple, inexpensive dustfall basin can be a subject of international agreement. In the meantime it is suggested that use of factors calculated from results such as are

[3] J. D. Sesenbough and W. C. L. Hemeon. American Society for Testing Materials. (1953).

TABLE II

Dustfall in Tons/sq. mile/month as recorded by gauges of the Toronto type and of the Detroit and International Joint Commission at one location

Month	Toronto Type	International Joint Commission	Ratio I.J.C.: Toronto
April 1955	36.1	65.0	1.8
May	27.6	50.8	1.8
June	22.8	50.5	2.2
July	16.6	28.5	1.7
Aug.	24.6[1]	45.0[2]	1.8
Sept.	16.5	31.0[2]	1.9
Oct.	29.4	47.4	1.6
Nov.	26.5	50.8	1.9
Dec.	20.7	35.9	1.7

(1) Overflowed
(2) Rim removed

TABLE III

Dustfall in Tons/sq. mile/month as recorded by 4 gauges of various types at one location

Type	Month				
	March	April	May	June	July
Toronto	36.2	24.8	40.2	19.3	21.6
British Standard	37.0	23.8	38.8	19.8	20.0
Detroit—I.J.C.	65.4	44.9	64.2	37.2	43.3
Pittsburgh—A.P.C.A.	—	31.3	56.5	40.7	26.4

TABLE IV

Dustfall in Tons/sq. mile/month as recorded by 2 identical gauges, one of which was washed 3 times weekly

	April	May	June	July
No washing	24.8	40.0	19.3	21.6
3 washes weekly	26.2	43.7	22.2	22.0

presented herewith, or more desirably an extension of those results, may provide a better indication of relative conditions between cities than would be obtained by a direct comparison of the published figures. This policy is that proposed by Sensenbough and Hemeon[3] as a means of adjusting for certain other variables.

The interest of Professor E. A. Allcut, formerly Chairman, Air Pollution Advisory Board, Toronto, and financial assistance from the City of Toronto in the conduct of a survey in which these determinations were made, is much appreciated. The technical assistance of Mr. J. Horwood and others has greatly facilitated this work.

The Fractionation of Dust Fall Samples by Physical Methods

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In the analysis of complex mixtures of solids by x-ray, spectroscopic and other techniques, the multiplicity of components offer serious problems. In order to reduce the complexity of the sample, fractionation procedures are necessary.

Two simple fractionation techniques, requiring a minimum of equipment and technical experience, have been applied to dust samples. These involve the separation of particles on the basis of the common physical properties of ferromagnetism and particle density. Fractions obtained, while not necessarily single components, are more easily analyzed. An added advantage is information which gives an indication of particle complexity rather than sample complexity.

In the investigation of dusts, it is desirable to obtain concentrations of similar components on the basis of their physical properties prior to x-ray, spectroscopic or other methods of analysis. Fractionation of such mechanical mixtures as dusts by non-chemical means must be a multiple process because of the number of components present; and it is often complicated by the fact that many of the particles are complex aggregates of varying composition.

This paper presents a technique for the separation of particles showing ferromagnetic properties from mixtures with non-magnetic particles; and also presents a method for the separation of non-magnetic particles on the basis of their difference in density. Although the equipment is inexpensive and the fractionation procedure simple to perform, the elemental analysis of the concentrates so obtained allow a better interpretation of the chemical nature of the different components of the dust.

Procedure

Magnetic Separations

The apparatus, shown in Fig. 1, consists of a small Alnico horseshoe magnet held by a non-ferrous clamp, a short length of soft iron rod (flat on one end and hemi-spherical on the other), a syringe or wash bottle, and several small containers (30 ml. porcelain casseroles are suitable).

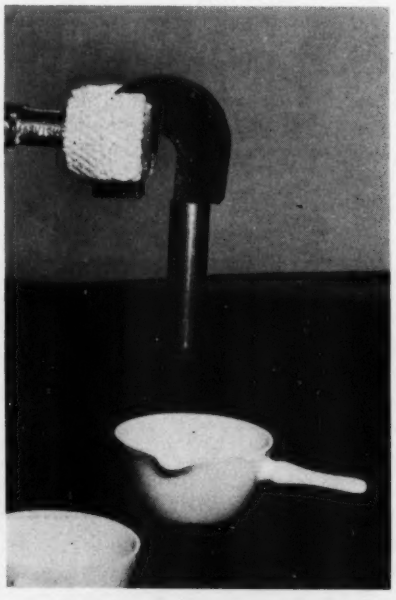

Fig. 1. Assembly for Separation of magnetic and non-magnetic components.

The flat end of the soft iron rod is attached to one arm of the magnet as shown in the figure. A weighed sample (0.5 to 1 gm.) of acetone-washed material is placed in the casserole and covered with acetone. The wetted material is contacted by the magnetized end which is then withdrawn. The particles adhering to the rod are gently washed with acetone to free trapped non-magnetic particles. The magnetic material held on the rod is then transferred by removing the rod from the magnet and allowing adhering material to drop into a casserole. *Removing the rod from the magnet, demagnetizes it as effectively as breaking the current does an electromagnet.* Particles held to the rod by residual magnetism may be removed by washing or by gently tapping the rod. The starting material is processed repeatedly in this manner until all of the ferromagnetic particles have been transferred. The material in the second casserole will also contain some trapped non-magnetics. It is covered with acetone and reprocessed in the same manner with the magnetic portions being transferred to a clean casserole. The collection on the magnet and transfer from one casserole to another are repeated until all of the material transfers, leaving nothing behind. The magnetic fraction is then dried and weighed. The non-magnetic fractions are combined, dried and weighed. The percentage of material recovered and percentage magnetics in the starting sample may be calculated. Results reproducible to within 2% can be obtained.

Separation of Dusts by Density

Separation of dusts, either non-magnetic or from which particles showing ferromagnetic properties have been removed into a number of similar fractions, is an aid in analysis and characterization. Physical separation of these materials may be made by utilizing the differences in density of the particles. If a dust or a mixture of powdered materials is placed in a density gradient column[1], concentration zones at various levels in the column will be obtained depending upon the density and, thereby, the composition of the particle. This gives an estimate of the range of densities and an approximation of the amount of material in each zone. However, where additional information is desired, another procedure was devised which yields separate fractions of the material. It uses only simple apparatus and a series of liquids that cover the density range, and depends upon the systematic processing of the mixture.

Two procedures for this systematic fractionation of dusts by difference in particle density have been used. One is based upon gravity separation in tubes and the other, a variation of the first, uses a centrifuge to reduce the time required for a given separation.

The only apparatus required for the separation is a series of separating tubes as shown in Fig. 2. Liquids used should have a low volatility, readily wet the sample, and cover the desired density range. One series of miscible liquids used in this laboratory to cover the range 1.9 through 2.9 gm./ml. was hexyl alcohol, ethylene bromide, and acetylene bromide.

Apparatus for the alternate procedure consists of a centrifuge, several small centrifuge tubes, the same series of liquids and a filter system. The filter system used was Pyrex glass Gooch filter crucibles with fritted discs, a suction flask and a source of moderate vacuum such as a water aspirator. Fine fritted filters were used for fine dusts, having particle size of less than 44 μ, and medium filters for larger particles.

In the gravity settling methods, the sample is pre-washed with one or more good organic solvents (soluble organic materials may be extracted and recovered if their further analysis as by chromatography[2] and other techniques are required). The sample is then dried and for a material balance weighed before separation. The sample and 10 ml. of the liquid of highest density are shaken in the separating tube, and then this suspension allowed to stand until the dusts separate into a top and a bottom fraction with little or no material in suspension. Dusts of relatively small particle size were found to require as much as 24 hr. settling time. For dust fall samples studied in this laboratory acetylene bromide with a density of 2.95 was used as the high density liquid.

After separation is complete by visual inspection, the bottom product is removed by very carefully opening the screw clamp, and allowing the heavy fraction to be washed out. If care is taken, the solids may be removed without remixing and without complete drainage of the liquid. The collected material is filtered, washed, dried and weighed. Using the pre-weighed glass filters, the weight of the sample is obtained by difference. The liquid remaining in the separating tube is carefully removed by manipulation of the screw clamp, leaving the solids in the tube. The next liquid in the series is added to the tube and the process is repeated until the fractionation is complete. If care is used in the drainage manipulation, the liquid left in the tubes each time will cause little change in the density of the succeeding liquid phase. Two series of liquids were used in this study, one of the series varied by 0.2 gm./ml. in density and the other by 0.4 gm./ml. The solutions were prepared by mixing pure materials and determining the density of the solutions in liquid pycnometers at 25°C.

The second technique, essentially the same as the first, uses an electrically driven clinical centrifuge and 15 ml. centrifuge tubes for small samples. The sample must be freed of air or other gases and thoroughly wetted with one of the lighter members of the liquid series before separation. Several wetting techniques were used. These included making the suspension in the lightest liquid to be used and then allowing it to stand for approximately 24 hr.; freezing the liquid suspension and pumping off the adsorbed gases with a vacuum pump; or evacuating the suspension using a water aspirator and then allowing it to come to atmospheric pressure, repeating the process several times. The latter is preferred because of its ease, and because the agreement between these methods was found to be within 2%.

After the sample is thoroughly wetted, it is introduced into a centrifuge tube, covered with the solution to be used, shaken thoroughly and then centrifuged. Time for complete separation is a function of particle size, for large particles (40 to 150 μ) 10 to 15

TABLE I

Results of Magnetic Separations of Whole Dusts

A. Material containing a low percentage of magnetics.

	Sample 1			Sample 2	
	Run 1	Run 2		Run 1	Run 2
% Mag.	0.9	1.0	% Mag.	7.0	6.9
% Non-Mag.	99.0	99.1	% Non-Mag.	92.0	92.5
% Recovery	99.9	100.1	% Recovery	99.0	99.4

B. Material containing a high percentage of magnetics.

	Run 1	Run 2		Run 1	Run 2
% Mag.	36.2	34.7	% Mag.	50.7	51.2
% Non-Mag.	62.8	64.4	% Non-Mag.	48.7	49.0
% Recovery	99.0	99.1	% Recovery	99.4	100.2

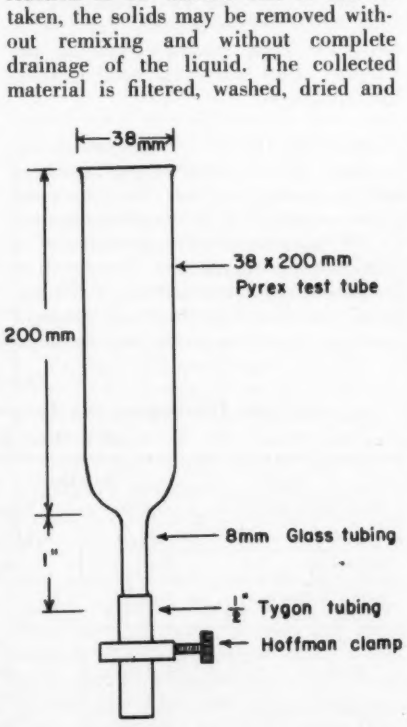

Fig. 2. Separation tube for the density settling method.

[1] N. Bauer, Chapter VI, p. 281 Physical Methods of Organic Chemistry, A Technique of Organic Chemistry, I, Part I, Weissberger, Editor, Interscience Publisher Inc., N. Y. (1949).

[2] R. L. Cooper, A. S. Lindsey, *Chem. and Ind.*, p. 1177 (1953).

min. is adequate. As particle size decreases, longer centrifuging time must be allowed, but for the present work no effort was made to work with extremely fine particles ($<1\ \mu$).

The top layer of the centrifuged material is recovered by decantation onto a fritted filter where it can be washed, dried, and weighed. For complete removal, it may be necessary to scrape out the last portion of the top layer that adheres to the walls with a spatula. Excess liquid in the tube is decanted, the liquid with next higher density added, complete dispersion brought about by shaking, and the centrifuging repeated. This procedure is followed until the sample is completely fractionated. The used liquids may be recovered by distillation and new solutions made.

Evaluation of the Separation Techniques

The results of magnetic separations are reproducible to within 2% as may be seen from Table I for samples containing from 1 to 50% magnetics. Some results of the application of the density separation method are given in Table II. For fractions obtained the maximum variation is 2.5%.

Since it was conceived possible that a dust fall sample having a wide range of particle sizes might give some composition change on sieving, separations were carried out on 2 samples sized $<44\mu$ and 44 to 150μ. The fraction containing particles larger than 150μ was not studied. The results are given in Table III.

From the table it may be seen that for the particles in the $<44\mu$ fractions, the weight percent of the higher density materials is greater than in the coarser fractions. The inference of this information to city dust problems is complicated and beyond the realm of this paper on separation methods. However, the significance of these results on the requirements for a representative sampling technique is readily apparent.

In the usual method of dust fall sampling by open container trapping, small samples are obtained and the analyses are made on the total sample except that it should be screened to remove particles greater than 150μ. For dusts collected in quantity, the sampling technique must insure a representative particle distribution. A modification of the coning and quartering method, [3] was used in this work.

[3] ASTM designation D 346-35; ASTM Book of Standards, Part 5, p. 882, (1952).

TABLE II
Results of Density Separations

Fraction	Run 1	Run 2	Difference
	Sample I		
	Percentage of Total Sample		
Magnetic	36.0	36.0	
Non-Magnetic (gm./ml.)			
>3.0	12.7	14.2	1.5
2.8-3.0	2.1	4.5	2.4
2.6-2.8	20.9	20.1	0.8
2.4-2.6	6.7	5.2	1.5
2.2-2.4	4.1	5.0	0.9
2.0-2.2	7.5	6.7	0.8
1.8-2.0	6.8	6.9	0.1
1.5-1.8	3.1	0.6	2.5
Recovery	99.9	100.2	
	Sample II		
	Run 1	Run 2	
Magnetic	1.8	1.5	0.3
Non-Magnetic (gm./ml.)			
>3.0			
2.6-3.0	79.1	77.1	
2.2-2.6	16.6	19.0	2.0
1.6-2.2	2.6	2.4	2.4
Recovery	100.1	100.0	0.2

The results of analysis for major constituents of the fraction in the 44 to 150μ region for sample II of Table III are given in Table IV. Analytical results for the other samples gave essentially the same results except for the quantity of the individual fractions from the separations.

In Table IV it is to be noted that overlap appears between the fractions, that is, 2 fractions may have the same major components. If the materials used in the separation were particles of a single composition, the fractionation would be complete and each of the materials would appear in exactly the right density fraction. However, since the particles are not of a single composition the fraction in which particles appear is the proper fraction for particles of that density. The overlap found does not invalidate the utility of the separation. Each fraction contains fewer components, gives a more quantitative picture of the dust as a whole, and allows for the detection of important constituents. It further provides a picture of the type of particles found in dusts in that a fused or fixed, mixed particle will have an average density representing its mixed components, and this may provide information as to its possible source.

TABLE III
Results Illustrating the Magnetic and Density Separations of 2 Dust Fall Samples

Fraction	Sample I		Sample II	
	Percentage of Sized Portion			
	($<44\mu$)	(44-150μ)	($<44\mu$)	(44-150μ)
Magnetic	21.8	16.3	32.7	20.7
Non-Magnetic (gm/ml.)				
>3	14.3	9.2	18.0	8.3
2.6-3.0	27.3	21.5	16.5	12.5
2.2-2.6	16.9	19.1	17.6	18.3
1.6-2.2	16.7	29.2	14.0	37.0
<1.6	3.0	4.8	1.9	2.7

TABLE IV

Major Constituents in 44-150 μ Fraction of Sample II, Table III

Fraction	Major Constituents
Magnetic	Fe_3O_4
Non-Magnetic (gm./ml.)	
>3.0	Fe_2O_3
2.6-3.0	Quartz, Mullite ($3Al_2O_3 \cdot 2SiO_2$) Mixed Silicates
2.2-2.6	Mullite, Quartz Mixed Silicates
1.6-2.2	Carbon: Clay
<1.6	Undetermined

Conclusions

Two methods of separations have been described which, when applied to the evaluation of city dusts, will aid in the study of community air pollution problems. A sized fraction of city dust fall sample was separated and analyzed for its major constituents to establish the ability of the technique to reduce the complexity without chemical change. That the methods do accomplish this is evident from the analysis for iron in the sample. Although perfect separations of chemical type are not obtained, a useful picture of the complexity of the particles is found.

Acknowledgement

The authors wish to gratefully acknowledge the financial aid furnished by the Industrial Hygiene Foundation, and the assistance of W. C. L. Hemeon and J. Deane Sensenbaugh of this Foundation in the valuation of the method by further analysis of the fractions.

Summary of the Conference on Odor Control *

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On October 25, 1956 under the auspices of the Cincinnati Bureau of Air Pollution Control in cooperation with The Engineering Society of Cincinnati and The Cincinnati Industrial Institute, a Symposium on Odor Evaluation and Odor Control was held in Cincinnati, Ohio. This paper by Mr. Stern summarizes the information presented at the symposium. Following this summary are several of the more pertinent papers, both in part and in full, as indicated, which were given during the conference.

Build-up of pollution in the air we breathe is prevented by turbulent mixing due to vertical and horizontal differences in air density. Some meteorological conditions suppress air mixing. An increase of temperature with height, called an *inversion*, suppresses vertical mixing. Because the warming and cooling of the lower air stratum depend upon the presence or absence of sun and clouds, a diurnal cycle results, with inversions forming on clear nights and being broken up by the heat of the daytime sun. Therefore, in hilly country like Greater Cincinnati, the diurnal maximum pollution occurs in the bases of our valleys just after sundown. Higher up the slope, the maximum occurs progressively later until about 2:00 a.m., and again about a half hour after sunrise.

Daytime break-up of the inversion may be prevented by compression by an incoming warm front or by a persistent stagnant high-pressure system. This latter is what caused the local *smog* of Oct. 15-16, 1956. Such conditions can be expected to occur about 3 times a year, during Indian Summer. These smogs are distinguishable from natural fogs in that the latter require more than 87% relative humidity, whereas this recent smog persisted after humidity dropped to 40% relative. However, because of increased nucleation of the atmosphere produced by human activities, fogs are now more frequent and persistent than several generations ago. The local air soiling index generally shows highest pollution early in the morning, and lowest around 2:00 p.m. The Cincinnati soiling index measured during the recent smog in Cincinnati was the highest since measurements began in 1952. Because of a combination of weather factors, most odor complaints occur between 8:00 p.m. and 2:00 a.m. on summer evenings and again soon after sunrise.

Abatement of odor sources requires both management support and technical know-how. Management, in accepting responsibility for such abatement, follows a 4 point plan: (1) **Learn the facts**—preferably in quantitative terms such as *odor units* of emission. (2) **Decide what to do**—determine what decrease in *odor units* is necessary to abate the nuisance. Assume that future standards

* Presented at the Metropolitan Conference on Air Pollution: Odor Control, Cincinnati, Ohio, October 25, 1956.

as to necessary abatement may be more stringent than present standards. Improvement in operating practices can sometimes effect as much as 30% improvement without adding any new equipment. (3) **Plan action on the basis of most economical scheme for abatement.** Evaluate economics on the basis of least cost/*odor unit* abated. (4) **Follow up action** to see that scheme is put into effect and kept operative.

The above plan puts considerable reliance on quantitative odor measurements. Both static and dynamic measurement methods are available, all involving dilution to odor threshold concentration and observation by trained persons who preferably should be chosen by screening to eliminate anyone with abnormal odor perception. Observers should be used as panels of several members rather than as individuals. The tendency of observers to try to outguess or outwit the test must be reckoned with in such subjective measurements and compensated for by the use of blanks and sufficient numbers of samples.

A prime odor control method is combustion, examples of which are the flare, the high temperature furnace, and catalytic combustion. Combustion can be used where the odorous contaminant is safely combustible and where the products of its combustion are not objectionable. Complete combustion of ash-free hydrocarbons to water vapor and carbon dioxide meets these specifications. Combustion of sulphur and ash-bearing substances can introduce objectionable substances to the atmosphere. Another control method is absorption, in a packed tower, spray column, spray chamber, or wet filter, usually having water or an aqueous solution as the absorbent. Disposal of the scrubbing liquid can present real difficulties and in solving an atmospheric odor problem, create a water pollution problem.

Chemical odorants, masking agents, or counteractants can be added both to industrial processes and to their effluent gases. Relatively small quantities of additives can change the odor observed in the neighborhood of the source and so eliminate some complaints. Similarly, discharge of odorous effluents from high stacks can decrease the frequency of odor complaints near a source. Since neither of these 2 methods of odor control reduces emission to the atmosphere, they do not prevent build-up of pollution concentration under a prolonged inversion ceiling.

Other odor control methods include adsorption of the odorous substance on a material such as activated carbon; process change to reduce the formation of odorous substances; and good housekeeping, to prevent the creation of odor from waste on floors, in dumps, and other unconfined areas.

Although there has been a 90% reduction in smoke emission in Cincinnati since 1947, the number of air pollution complaints has doubled in the last 5 yrs. In 1955 more than half these complaints were of odor. Abatement of odor sources is accomplished in Ohio municipalities by exercise of the police power of local governmental authorities which allows them to abate various classes of nuisances. Final determination of the existence and classification of these nuisances requires administrative or court decision as to what constitutes a *substantial* number of persons affected and the *reasonable* use of private property. The corrective procedure used involves the successive steps of (1) investigation, (2) administrative hearing, (3) abatement order, (4) correction of condition. Another approach is to prevent the installation of new odor sources by compulsory filing of plans for approval prior to construction, and by zoning. Major problems in zoning are nonconforming use of land because of prior existence in the newly zoned area and the intrusion of higher type land-use (*i.e.* residential into zones of lower grade use.

Abatement of odor sources in the Cincinnati metropolitan area presents a serious governmental problem. The City of Cincinnati is only one of 50 jurisdictions in a metropolitan area of a million people. Although consolidation or annexation to form a major area governmental unit is perhaps considered the ideal political solution, the realities of the situation suggest that a plan for action now can be achieved within the framework of local home rule for all communities involved. A 4-point approach is:

(1) Set up a voluntary air pollution control district for the jointly affected Kentucky and Ohio communities;

(2) Implement this in the Kentucky communities by further action under the State law allowing counties to organize themselves into Air Pollution Control Districts;

(3) Have all the communities adopt a uniform air pollution ordinance;

(4) Undertake an integrated area study and research program by arranging for the smaller Ohio communities to contribute financially toward the support of activity by Cincinnati-based air pollution control personnel studying all of the local problems.

The salient point to remember in this, as in most other air pollution problems is that as Greater Cincinnati is rapidly growing in population, progressively more domestic, industrial, and automotive effluents are being confined in the lower hundred ft. of the atmosphere whenever we have a persistent inversion ceiling. An indication of the magnitude of the odor problem lies in the fact that 30% of manufacturing industry in this urban complex is in the chemical and food category. These sources, added to those from waste disposal and motor vehicle exhaust, make up much of our local problem. Unless each source in the future contributes less pollution, the total pollution thus confined must, of necessity, increase, resulting in more frequent and more intense *smogs* in Cincinnati. The corollary is that the standard for acceptable emission /source must over the years become progressively more stringent.

Rank Odor Method for Evaluating Stack Gases*

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The problem of measuring the amount of obnoxious material removed from gases discharged in the atmosphere is inherent in many attempts to solve air pollution. While instrumental methods have been developed for the measurement of particulate matter, only those odors derived from a single simple substance can be subjected in a quantitative type of measurement.

The following simple procedure for evaluating odors in stack gases proved to be quite reliable. Since it may be applicable in other instances it is being reported.

In this specific case the relative effectiveness of a scrubber in removing odors from stack gases was being evaluated. Sampling trains were connected to the exhaust systems before and after the scrubber. Comprising these trains were entrainment separators, and 2 freeze-out traps. Equal volumes of gas were passed through the respective sampling trains at equal rates. Effluents from the freeze-out traps were completely odorless. The freeze-out samples were diluted to equal volumes so that subsequently a 1 ml. sample of either freeze-out represented equal quantities of exhaust, scrubbed or unscrubbed.

A concentration approaching but above the threshold level was determined on the freeze-out from the unscrubbed gas by submitting various dilutions of the material to the test panel. These were submitted to the panel in coded 250 ml. glass-stoppered, red Erlenmeyer flasks. One hundred ml. portions were used in the flasks. Each tester received 4 flasks containing 3 different dilutions and 1 distilled water blank. Testers were asked to rank the coded samples with a 1, 2, 3, 4, order, assigning a value of 1 to the sample with the most odor and a value of 4 to the one with the least odor. The scores obtained by the respective samples were totaled. These sums were used to indicate a concentration of the freeze-out which could be readily detected yet would not be sufficiently strong to deaden the sense of smell. The concentration determined above was then used in subsequent rank order tests in which various dilutions of the freeze-out from the scrubbed gas were compared with it.

One of the series of tests which was used is given as an example of the procedure: Samples used in the test were a 1/300 dilution before scrubbing, 1/100 after, 1/50 after and 1/25 after. These, of course, were coded and were submitted on a blind basis. As before, testers were asked to rank them 1, 2, 3 and 4 with the strongest odor first and the least odor last. The sums of the ranks assigned to the 4 respective samples by the 27 panel members were:

1/300 before
61

1/100 after
93

1/50 after
73

1/25 after
43

An analysis of these values indicated that the testers detected a significant difference between the samples. Based on the values in this test as well as others not illustrated here, the 1/300 dilution before scrubbing was considered by the testers to have an odor intensity somewhere between a 1/25 and a 1/50 dilution of the after scrubbing freeze-out. Thus it was concluded that the scrubber had reduced the odor constituents of the stack gases to between 1/6 and 1/12 of the original concentration. Combining this with other similar data it was concluded that the odor was reduced to roughly 1/10 of the original.

*Presented at the Metropolitan Cincinnati Conference on Air Pollution Control, Odor Control, October 25, 1956.

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Odor Pollution Problems from the Control Officials' Viewpoint*

CHARLES W. GRUBER
City of Cincinnati
Cincinnati, Ohio

While Air Pollution Inspectors from our Bureau make *odor observations* in the field, an odor situation generally starts with a complaint from a resident. From then on, it becomes a matter of investigation, evaluation and action.

Strong or obnoxious odors are dealt with under Section 2501-3(b) of the Cincinnati Air Pollution Ordinance. The section reads as follows:

> **Section 2501-3(b). Acid or other fumes, noxious gases, strong odors, dust, dirt or other solids in quantities (defined in Section 2501-5) emitted or allowed to escape in such place or manner as to cause injury, annoyance or detriment to the public, or to any person or to endanger the health or safety of such a person or the public, or emitted in such a manner as to cause injury or damage to business or property, are hereby declared a nuisance and the emission or escape thereof from any stack, or chimney, window, door or other opening, ventilating device, or from any building, premises or other source, shall be unlawful.**

It is to be noted that the enforcement methods dealing with the air pollution nuisances is entirely different from the procedures in dealing with visible smoke. A standard of comparison is established for visible smoke discharge. The ordinance includes a description of the instrument to be used in the measurement of dense smoke. This instrument in the case of the Cincinnati Ordinance is the Umbrascope, and in the case of many ordinances throughout the country, is the Ringelmann Chart. However, air pollution nuisances including odors are described by adjectives, such as strong, offensive, obnoxious, *etc.* Therefore, the evaluation of the nuisance must be in accordance with these terms.

Finding the Odor Source

The odor situation is not so difficult to handle when the source is a well-defined continuous process running day in and day out, so that the odor pollution level rises in a particular neighborhood with a degree of regularity whenever the weather influences are right . . . that is, when a straight flowing air stream carries the pollutants in a well-defined fan-like directional pattern to the affected neighborhood downstream from the plant, or when a stagnant air mass forms under a low level temperature inversion layer, causing the pollutants to mushroom over an entire area. However, when the offending source is a 1 or 2 batch process from among many, or when different materials processed through the same equipment result in foul smelling discharges one time and perfumed fragrance another, so that the odor emissions are spasmotic, catching or missing weather conditions to cause odor build-up without pattern or cyclic recurrences, it is harder to analyze the situation than to pick out the shell that covers the pea at the carnival.

Evaluating the Odor Situation

Here is where judgment, patience and tact are required. It is in this field that we have our biggest need . . . the need for some type of instrumentation or technique which permits the inspector to more and less objectively evaluate an odor intensity situation.

The really big question is how much odor removal is necessary to warrant the stamp of acceptability by the neighbors of the offending source. 100% odor removal is a fine goal to shoot at. However, can this situation always be obtained and still permit industry to operate? Can industry operate with no offensive or strong odor emission? I think all will agree that this must be done. Which brings us directly to the definition of *strong or offensive.* It is a well-known fact that what is offensive to one person will not be offensive to another or what is strong in the mind of one person will not be strong in the mind of another.

So, we have great need for the instrument which will permit some degree of objectivity in odor evaluation. It was noted in the daily press recently under the column, *Inventors' Needs* that the Federal Government wants a *mechanical nose* for detection of odors in aircraft for safety measures. Our need for the *mechanical nose* is no less urgent.

In the development of the odor measuring device, it has been my feeling that we have been demanding too much accuracy or preciseness in the initial endeavor. We might draw from the book of history in smoke abatement work, wherein the Ringelmann Chart designed some 50 yrs. ago as a means of evaluating visible discharge is still in general use. The Ringelmann Chart has many drawbacks from a practical application, but it has served well in the field of smoke abatement. It is my feeling that if our goal is to evaluate with a *yard stick,* rather than with a *micrometer,* there will be much more chance of development. The methods of odor measurement or evaluation which will be demonstrated at this conference, are an excellent start in this direction.

What Can Be Done about an Odor Situation

There are many approaches to the prevention of discharge of bad odors. We have a wealth of case histories in which specific odor sources were eliminated by the application of one or more of the known methods. However, from our observation, the place to start first is housekeeping, control of processes, and an intense education of equipment operators. After this, then look to odor removal equipment.

Odor Monitoring Runs

While most of our odor enforcement work starts with odor complaints, for several years we periodically have operated odor monitoring runs. A route of approximately 25 miles in length has been laid out, which takes an inspector through the areas from which most odor complaints are received. The odor runs are conducted in the evening as experience indicates that odor complaints are most likely to find their origin in conditions which occur after sundown. Each inspector who starts on an

Excerpts from a paper presented at the Metropolitan Cincinnati Conference on Air Pollution Control, Oct. 25, 1956, Cincinnati, Ohio.

odor route has a form on which to record his observations. He has been instructed in the standard terminology and technique of recording the odor observation. Any strong odor situations observed during the run are followed up in accordance with a set policy.

Conclusions

In conclusion, I wish to make a few observations about the air around us. The actual air is not confined in pipes, ducts or streams, but flows in one direction and then another as the winds blow. And, thus, people who live in the vicinity of an irresponsible user are inevitably caught in the aerial sewer. Therefore, people and industry must use the outdoor air with care and consideration, so that the next person to use it to sustain life or produce a product, will not be harmed. The outdoor air is not free. It must be paid for by proper cleansing before it is given back to nature.

The challenge to this conference today is to pool our store of knowledge or how odor pollution can best be prevented from spoiling our most precious natural resource.

A Management Approach to Odor Control*

R. H. FINK
The Proctor and Gamble Co.
Cincinnati, Ohio

Modern management recognizes that control of industrial odors is an established responsibility of business. Management interest and sincerity are demonstrated by the millions of dollars which are spent each year on odor control. However, there is much more to be done. It must be remembered that what has been done today will not be good enough for tomorrow and what is not good enough today soon will be intolerable. This is the price of progress.

It is a well known fact that people have become more and more aware of air pollution and are actively campaigning for improvements. The trend toward better living is obvious in every phase of community life. It is evident in projects for better schools, cleaner rivers, bigger hospitals, and all forms of social welfare. Our business men and our companies are actively supporting these projects and assuming leadership responsibilities.

The problem is not only a local one but is of national importance as indicated by the Federal Air Pollution and Technical Assistance Act of 1956. This became Public Law 159 during the 84th Congress.

Just as management learned through experience to incorporate safety devices on all equipment, progressive management today insists that odor control be designed into all processes. Progressive management demands that objectionable odor be eliminated.

The approach which management takes towards odor control varies widely between industries and companies. There are, however, several key steps which seem fundamental.

1. Management must know the facts concerning odors from its business and how they effect the people of the community.

   Learning the facts is not always easy when you have lived with traditional odors. You can assume, however, that odors of any description are basically objectionable to the residents in the vicinity of the operations. The odors may smell like Grandmother's home made bread or apple pie, but the people in the neighborhood will consider them foreign and, therefore, objectionable. To know what odors find their way to various neighborhoods, some industries have established regular tours to evaluate the significance of their odor emissions. When speaking of facts, figures are always needed. This applies to odor control. Once the sources of odors in a factory are determined, it is important to measure the intensity and amount of odor on a quantitative basis. Engineers have learned to put odors in quantitative terms.

   Direct quantitative measurements of odor is an engineering tool frequently used in manufacturing processes. This is a relatively simple technique which has been a great help in evaluating odors and designing odor control equipment. The convention used is an *odor unit*. An odor unit indicates the intensity of the odor. An odor unit is the ratio of fresh air needed to dilute the odor to a threshhold or barely preceptible level. To determine the odor units/min. it is necessary to measure the cfm. in the conventional manner. The intensity times volume gives emission in odor units/min. For example, if an odor source is found to have an intensity of 10 odor units and the rate of flow is 20 ft.^{3}/min., the odor output is 200 odor units/min. This method was described in detail in the magazine, *Chemical and Engineering News*, June 4, 1956 issue.

   Modern management today does not wait for a rash of complaints from neighbors to learn the facts. A technical analysis of the situation is used to determine factual information.

2. Once the odor sources are measured, a study is then made of the corrective procedures and equipment. In most cases there are established odor control processes and equipment that can materially reduce odors. The larger companies generally have technical people who are qualified to evaluate odor control measures. Outside assistance is available from city, state and federal officers as well as any number of commercial consultants and suppliers. This afternoon you will hear a review of the technical aspects of several types of odor control equipment. To the engineer, odors can be controlled if given sufficient time and money.

   One of the quickest and least expensive opportunities for controlling odors is through improved operating techniques. Like any other manufacturing variable, when little or no

*Presented at the Metropolitan Cincinnati Conference on Air Pollution Control, Odor Control, October 25, 1956.

emphasis has been placed on it in the past a 20 or 30% improvement is often available through better operating techniques. The men on the jobs in the factory can generally find a way to improve operations to reduce odors if urged and encouraged to do so. If less odor is made, equipment is not needed to destroy, to disperse, or to counteract it.

3. Once the source of odors is listed and corrective measures outlined, management can set up a plan of action for odor control. Much judgment is required to evaluate how far to go in such a program, how much money and effort is justifiable for odor control. The proper answer is generally *further than you think.* This is a long range effort. It is safe to assume that the odor criterion of the future will be a great deal more rigid than the present.

   A proper management decision can best be made if the facts such as we have outlined are listed on a quantitative basis. If the corrective measures can be set down in terms of cost/odor unit reduction, a better analysis can be made and more justifiable decisions reached.

4. Every manager knows that no program, no matter how forcefully initiated, will continue purely on its own momentum. An odor control program requires continuous management follow-up. Responsibilities must be established and the operating and technical people must know that control of odors is an important part of their job. Certainly items such as cost or quality or safety do not automatically take care of themselves. Management must keep the control of odors as an established business responsibility and impose self discipline upon itself.

It is extremely ambitious, of course, to attempt to review management's viewpoint on any subject in a few minutes, but I would like to leave you with the following summary of management's approach to odor control.

Management today recognizes and accepts the control of industrial odors as an established major business responsibility.

Management approaches odor control by:

1. Measuring odor sources using quantitative engineering techniques.
2. Studying the appropriate corrective action.
3. Establishing an aggressive control program with well defined organizational responsibilities.
4. Following up on a continuous basis to be positive that the organization is living up to its responsibilities to its neighbors.

These principles are not new to management. There are no panaceas. However, an approach such at this, if applied with vigor and sincerity, will contribute to the *better living* in our communities that is so vital to us all.

Demonstration -- Syringe Odor Measurement Technique*

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Odor measurement is based upon the simple idea of taking an odorous gas and diluting it with clean air until the odor is barely detectable at the so-called odor threshold level. The ratio of clean air to odorous air necessary to reach this threshold value is the measure of the amount of odor in a given source. The larger the amount of clean air necessary to dilute the odorous material down to the threshold value, the greater is the odor intensity. A question which sometimes arises is why bother diluting but merely inhale the odor and judge the intensity. Unfortunately, the characteristics of the sense of smell preclude this approach. The olfactory nerves are extremely sensitive in detecting the presence of a substance in very minute quantities. However, as the intensity increases, the nose is incapable of judging quantitatively the extent of the increase. In fact, a considerable change in quantity of odor is necessary before the olfactory nerves react to the increase or decrease. Also as the odors get more intense, the sensitivity of the nose quickly drops, due to olfactory fatigue. In a nutshell, the nose is a good qualitative instrument but not a good quantitative instrument. Hence the need for diluting down to the threshold odor and determining the intensity of odor by the dilution ratio required to reach this threshold.

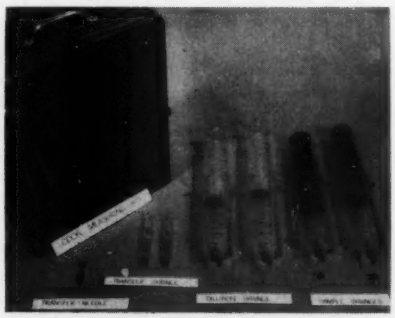

Fig. 1

Since we are measuring odor, let's define our units of measurement. We have established the odor unit and defined 1 odor unit as the amount of odor necessary to contaminate 1 ft.^{3} of clean air to the threshold or barely perceptible level. This merely means that if a certain emission contained say, 5 odor units/ft.^{3}, then we can take 1 ft.^{3} of sample, add 4 ft.^{3} of odor free air, and come up with a resultant mixture which has a barely detectable odor. If to this same emission we added, say, 6 ft.^{3} of odor free air then the odor could not be detected. The syringes used in odor concentration determinations (Fig. 1)

* Presented at the Metropolitan Cincinnati Conference on Air Pollution Control, Oct. 25, 1956, Cincinnati, Ohio.

Fig. 2

Fig. 3

Fig. 4

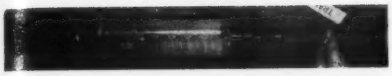

Fig. 5

are nothing more than a means for diluting the odorous materials with a measurable quantity of clean air. The syringes are standard medical units which can be obtained at any medical supply house. The 1½ to 3 in. needles are required so that the odorous material can be withdrawn from well within the duct or stack.

After the sample is taken from the duct or stack, the needle is removed and the cap placed on the syringe to avoid losing any sample. The sample syringe (Fig. 2) is taken to an odor free room where clean air is available to make dilutions. The ground joints of the glass syringe are extremely tight. None of the sample can leak to the atmosphere.

At this point we need an odor panel of several people. The number of people on the panel can be varied to suit the purpose of the test. Accuracy and reproducibility of results can be increased by increasing the number of observers. Normally for a survey of the odors of an entire plant where only a general, over-all picture of the situation is desired, we have successfully used 3 men. The panel should be carefully screened. Many people have a very poor sense of smell. Others may be highly imaginative. The people on our panel generally check rather closely.

In order to establish an order of magnitude, normally samples of 9:1, 99:1 and 999:1 are prepared. If the observer cannot smell the 9:1 dilution, we know the odor level is less than 10 odor units/ft.^{3} and further dilution in the lower range will be made. If the observers can smell to 9:1 sample but detects no odor in the 99:1; then we know the range of the odor intensity lies between 10 odor units/ft.^{3} and 100 odor units/ft.^{3}. In this case we will further narrow the range by preparing dilution of say 25:1, 50:1 and 75:1. On the other hand, if the panel detected odor in the 99:1 sample, but could observe no odor in the 999:1 dilution we know that the odor intensity is between 100 units/ft.^{3} and 1000 units.

How are these 3 samples prepared? For the 9:1 dilution we merely transfer 10 cc. of the odorous material from the sample syringe to the mixing or dilution syringe. Then we can draw in 90 cc. of the room air into the dilution syringe assuming it is odor free. The marks on the syringes are in 10 cc. increments so this is easily done.

Next let's prepare the 99:1 mixture. How is 1 cc. of odorous material transferred from the sample syringe to the dilution syringe when 1 cc. increments are not marked? One way is to use the small 3 cc. syringe. Withdraw 1 cc. of odorous gas from the sample syringe with the 3 cc. transfer syringe. (Fig. 3) Then inject 1 cc. into the dilution syringe and draw in odor free room air to the 100 cc. mark on the dilution syringe. (Fig. 4 and 5)

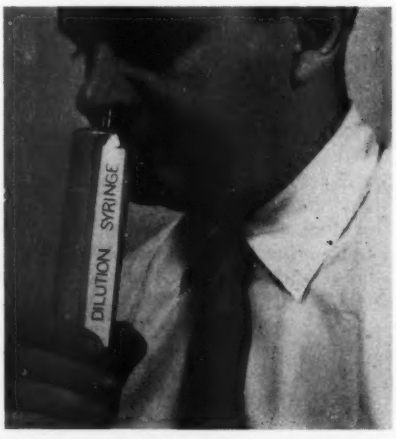

Fig. 6

The 999:1 dilution is prepared in the same manner except the last step consists of ejecting 90 cc. of the 99:1 mixture and drawing in 90 cc. of fresh air. We now have 3 samples prepared for 1 member of the odor panel.

The samples should not be handed to the member in ascending or descending order or he will catch on to the pattern and try to second guess or outguess the samples. The observer should never know which sample is being tested nor the dilution ratio of the particular sample under test. In addition, an occasional blank thrown in keeps the panel *loosened up, honest* and on their toes. The observers are supposed to *smell* and not *think*.

Note the observer uncaps the dilution syringe and inserts the tip of the syringe into 1 nostril. (Fig. 6). He suspends breathing and expels the 100 cc. of diluted samples into the nostril at a uniform rate over a 2 to 3 sec. period. The observer then states whether or not any odor was detected.

The observers should abstain from smoking or eating about 30 min. prior to the tests if possible for better results. Members of the panel with colds should not participate in the tests.

The precision and accuracy of this method depends on the number, physical condition, experience and skill of the observers. Every single observer should be able to attain results which are reproducible with 50% on any given day. Where greater accuracy is desirable for any given test, more observers should be used, and their results averaged.

Acknowledgment

Credit is due Messrs. V. E. Gex and E. A. Fox of Procter & Gamble for their contributions to the development of the syringe technique of odor measurement (see following article).

Procedure for Measuring Odor Concentration in Air and Gases*

E. A. FOX and V. E. GEX
The Proctor and Gamble Co.
Cincinnati, Ohio

Scope and Application

1. (a) This method covers a procedure for determining the odor concentration in the atmosphere and in gases discharged from industrial process operations, and for determining the odor emission rate from a stack or vent. It establishes a quantitative concept of odor, whereby the relative quantities of odor from 2 or more different sources, or from the same sources under different operating conditions, can be compared.

(b) This method is intended as a quick, practical way of measuring odor concentrations. It depends upon the human olfactory sense, and is subject to the variations of this sense, from person to person, or from hour to hour in the same person. Accuracy and reproducibility of results can be increased by increasing the number of observers; this can be varied to suit the purposes of the test.

Summary of Method

2. (a) A sample of the atmosphere or gas whose odor is to be measured is diluted with odor-free air until a dilution is achieved in which the odor can barely be perceived. The ratio of the total volume of this diluted sample (sample volume plus volume of diluting air) to the volume of original sample in the diluted sample is a measure of the concentration of odor in the original sample.

(b) The technique described assumes that the odor concentration is to be measured without regard to the material or materials which cause the odor, or the concentration of these causants in the sample. It does not take into account the character of an odor.

Definitions

3. (a) Odor Unit — The quantity of odor in 1 ft.^{3} of air which has been mixed with an odorous substance to the point at which the odor is barely preceptible in the mixture (odor threshold).

(b) Odor Concentration—The number of odor units in 1 ft.^{3} of odorous sample. It is equal to the threshold odor concentration (1 odor unit/ft.^{3}) times the threshold dilution ratio V_d/V_s, where V_s is the volume of original sample and V_d is the volume of sample after dilution to the odor threshold. It is a measure of the total volume of air which 1 ft.^{3} of the sample will contaminate to the odor threshold. It is expressed in odor unit/ft.^{3}

(c) Odor Emission Rate—The number of odor units discharged from a stack or vent/min. It is the product of the odor concentration of the discharge gas, and the volume rate of discharge, in ft.^{3}/min.

Interferences

4. (a) Extraneous odors and lingering taste effects interfere with this test. The area for the test must be clean, free of odors, and quiet. Hands and clothing of the observer, and equipment used in the test, must be clean and free from odor. Smoking, chewing of tobacco or gum, or eating should not be indulged in for at least 30 min. prior to the determination of odor concentration.

(b) Poor physical condition of the observer may interfere with this test. The observer must be free of *colds* or other physical conditions affecting the sense of smell. No observer shall carry out odor tests for longer than 15 min. at a time, and he shall rest a like period before resuming such tests.

(c) Not all observers are capable of carrying out this test. A group of at least twice the number of observers required shall be screened to select the most sensitive individuals for observers. A suitable screening test consists of a *triangle* test in which 2 identical and 1 odd sample, such as vanillin, and methyl salicylate, each dissolved in the odorless diluent, benzyl benzoate, are presented to the observed in increasingly dilute concentrations, starting with a 1.0% solution. The observer is scored on his ability to distinguish the odd odorant from the 2 identical ones, as the dilution increases. The members of the group with poorest olfactory perception shall be eliminated by this test, and the individuals with better olfactory perception shall be selected as observers.

Apparatus

5. (a) Sampling Syringe—2 or more 100-ml. Luer type hypodermic syringes.

(b) Dilution Syringe—1 or more 100-ml. Luer type hypodermic syringes.
(identical to sampling syringes).

(c) Transfer Syringe—2 or more 2-ml. Luer type hydopermic syringes and 1 100-ml. Luer type hypodermic syringe.

(d) Transfer Needle—a fitting for connecting the transfer syringe with the sampling and dilution syringes. It is made from 2 standard 25 gage BD hypodermic needles, 1½ in. long. The mating head of 1 needle is cut off at a point where its inside bore is equal to the outside diam. of the needle shaft. This mating head is slid over the second needle, with the mating opening toward the tip of the needle, and silver-soldered in place.

(e) Syringe Caps—1 Luer syringe cap for each syringe.

(f) Odor-free Room — Maintained at comfortable temperature and humidity conditions.

*Presented at the Metropolitan Cincinnati Conference on Air Pollution Control, October 25, 1956, Cincinnati, Ohio.

Reagents

6. Odor-free Air.

Sampling

7. (a) Fill 2 sampling syringes with the air or gas whose odor concentration is to be measured, by pushing the plunger all the way in, inserting the tip into the atmosphere to be sampled, and pulling the plunger out to the 100-ml. mark. Place caps over the tips of the syringes, and transfer them to the odor-free room for the determination of odor concentration.

Procedure

8. (a) Thoroughly scrub all syringes and transfer needles with an unperfumed detergent. Rinse thoroughly in odor-free tap water, wipe dry with a clean cloth, and allow to dry in the test room atmosphere for at least 15 min.

(b) Dilution samples are prepared only by an assistant to the observer, and given to the observer for smelling. In preparing the dilution, place the transfer needle on the transfer syringe, remove the cap from the sampling syringe, and with the transfer syringe empty, insert the transfer needle tip into the sample syringe, and tightly connect the 2 syringes together. Withdraw the desired volume (V_s) of the sample into the transfer syringe. Withdraw the needle from the sampling syringe, and recap the latter. Insert the transfer needle tip into the dilution syringe, partially filled with odor-free air, and inject the sample volume (V_s) into the dilution syringe. Withdraw the transfer needle from the dilution syringe, fill the dilution syringe to the 100-ml. mark with odor-free air, cap it, and allow it to stand for at least 15 sec. to allow mixing by diffusion. The diluted sample is then ready for testing by the observer. If volumes for V_s of 2-ml. or less are required, use the 2-ml. transfer syringe. If volumes greater than 2-ml. are required, use the 100-ml. transfer syringe. If volumes less than 0.2 ml. are required for V_s, make an intermediate dilution of 1:9 by drawing 0.2-ml. of sample into a clean 2-ml. syringe, filling it with odor-free air to the 2-ml. mark, and injecting a portion of the intermediate dilution into the dilution syringe; for such tests, the sample volume V_s will be 1/10 of the intermediate dilution used.

(c) Without prior knowledge of the degree of sample dilution, uncap the dilution syringe and insert the tip of the syringe into 1 nostril. Suspend breathing for a few sec., and during this period expel the 100-ml. diluted sample into the nostril at a uniform rate over 2 to 3 sec. Record whether odor is perceived in the diluted sample. If odor is perceived, purge the dilution syringe with odor-free air until odor can no longer be detected in it. If the syringe cannot be purged of odor, clean it as in paragraph (a), or use another clean syringe for the next dilution.

(d) To establish order of magnitude of odor concentration of the sample, prepare samples of 1:9, 1:99, 1:999, and 1:9,999 dilutions in random order as described in paragraph (b). Note the greatest dilution at which odor is perceived.

(e) Based on the results obtained in (d), prepare a series of dilutions in the range between the greatest dilution in which odor was perceived in (d) and the next greatest dilution in (d). The order of dilutions should be random, and at least one out of any four consecutive dilutions should be a *scramble* dilution, in no way related to the fundamental trend. The *scramble* dilution may range from no odor to one considerably above the threshold concentration. In this manner, the observer is assured that he cannot anticipate what the next concentration will be; he must concentrate only on whether he perceives or fails to perceive the odor on any given sample.

(f) Proceed as in (e) until the difference between the *greatest dilution at which odor is consistently perceived and the next greatest dilution measured is* less than 50% of the greatest dilution at which it is consistently perceived.

(g) If the sample being analyzed is from a stack or vent, and the odor emission rate from the stack or vent is desired, determine the average velocity of discharge from the stack or vent, in ft./min., employing one of the methods described in the *Heating, Ventilating, and Air-Conditioning Guide*, 29th Edition, pages 1027 to 1032. Determine the inside cross sectional area of the duct or stack, in ft.^{2}

Calculations

9. (a) Calculate the odor concentration, in terms of odor units/ft.^{3}, as follows:

$$C = \frac{100}{V_s} \times (1 \text{ odor unit/ft.}^3)$$

where:

C=*odor concentration of original sample, odor units/ft.*^{3}

V_s=*ml. of original sample present in the most dilute sample in which odor is perceptible in Section* 8 *(f) above.*

100=*ml. of diluted sample in Section* 8 *(f) above, and (1 odor unit/ft.*^{3}*) = number of odor units/ft.*^{3}*) in diluted sample at the odor threshold.*

(b) Calculate the odor emission rate, in terms of odor units/min. as follows:

$$\text{Odor Emission Rate} = CVA$$

where:

C=*odor concentration, odor units/ft.*^{3}*, as determined in Section* 9 *(a), above.*

V=*velocity of stack or vent discharge, ft./min., as determined in Section* 8 *(g), above.*

A=*inside cross sectional area of stack or vent, ft.*^{2}*, as determined in Section* 8 *(g) above.*

Precision and Accuracy

The precision and accuracy of this method depend on the number, physical condition, experience, and skill of the observer. Any single observer should be able to attain results which are reproducible within ±50%, on any given day. Where greater accuracy is desired, for any given test, more observers should be used, and their results averaged.

Air Pollution Problems of the Steel Industry
Technical Coordinating Committee T-6 Steel Report

Dust Problems in Blast Furnace Operation

WESLEY C. L. HEMEON, *Editor*

Outline of the Blast Furnace Process

The following description of the blast furnace process is taken from *The Making, Shaping and Treating of Steel.*[1]

"Essentially, the blast-furnace process consists of charging iron ore, fuel (coke) and flux (limestone and dolomite) into the top of the furnace and blowing heated air (blast) into the bottom. A rough statement of the input of each material/ton of iron produced would be 2.0 tons of ore and iron-bearing materials, 0.9 ton of coke, 0.4 ton of a mixture of limestone and dolomite, and 3.5 tons of air. From these materials there is produced 1.0 ton of iron, 0.6 ton of slag, 0.1 ton of flue dust and 5.1 tons of blast-furnace gas. These figures are for present materials which are available to the territory that borders the Great Lakes and which produces about 75% of the pig iron in the United States.

"The function of the ore, as well as the other iron-bearing materials, is to supply the element iron which, in turn, represents about 93½% of the pig iron. The ore is usually in the form of the oxide, either hematite ($Fe2O_3$) or magnetite (Fe_3O_4), although there may be small proportions of limonite ($2\ Fe_2O_3 \cdot 3H_2O$) or siderite ($FeCO_3$) present. Hematite represents the largest proportion and usually comes from the Lake Superior region. When chemically pure, hematite contains 70% iron, but the present ore contains about 50% iron, the difference being represented by gangue which consists mostly of silica and alumina and about 12% moisture.

"Other iron-bearing materials are mill-scale, sinter, slag from open-hearth furnaces or Bessemer converters, and scrap. Scale (Fe_2O_3) is a by-product of the rolling operation which drops from the piece as it passes through the rolls. Sinter is blast-furnace flue dust (or a mixture therewith of fine ore) which has been sintered to form a granular, relatively coarse material. . . .

"The function of the coke is 2-fold: first, to supply sufficient temperature for the metallurgical reducing reactions to take place; and second, to supply the reducing agent for the reduction process. Sufficient temperature is necessary to reduce and melt practically all the iron, most of the manganese, and a small part of the silicon, and to flux and melt the gangue of the ore and the ash of the coke. The incandescent carbon of the coke is inherently a strong reducing agent, and it is thought, itself, to account for about 20% of the reduction taking place in the blast furnace.

"The oxygen of the blast unites almost immediately on entering the furnace with the carbon of the coke to form carbon monoxide, which accounts for the balance (perhaps 80%) of the reduction taking place.

"The function of the limestone and dolomite is to form a fluid slag of a composition which will restrict appropriately the other elements (silicon, sulphur, *etc.*) entering the pig iron. These so-called metalloids in turn also control, within limitations, the mechanical and chemical properties of the pig iron. . . .

"Parts of a Blast-Furnace Plant. The heart of the apparatus is, of course, the blast-furnace structure itself. The sections of the furnace are (1) the lowest part, known as the *hearth*, (2) the inverted frustrum of a cone immediately above it known as the *bosh*, and (3) the part known as the *stack* or *shaft*. Means are provided at the bottom for the admission of the blast and removal of iron and slag; at the top, apparatus is provided for the charging of the ore, coke, and flux and for the removal of the gas generated in the process. The gas is led to the *dustcatcher* for the mechanical separation of the major portion of the dust; thence, through the *primary* and *secondary cleaners* it is conducted away for use in metallurgical heating, the generation of steam under boilers, or to operate blowing engines. The *blast* air is compressed by turbo blowers, steam engines, or gas engines, and driven to the *stoves* wherein it is heated regeneratively before its entry into the upper part of the furnace hearth. Bins for the storage and selection of the proper proportions of ore, coke, and flux are provided together with means for conveying these materials to the top of the furnace. Incoming materials arriving in railroad cars are either unloaded directly into the bins or by a car dumper from which they are handled for storage by an ore bridge. Incoming materials in boats are handled either by Hulett unloaders, belt conveyors, or modified ore bridges. The molten iron is carried away from the furnace in *iron ladles* which deliver it to the steel-making or foundry departments for use in the molten condition, or to the pig machine where it is cast into small blocks for use in the solid condition. The slag is either disposed of molten in *cinder ladles* or granulated by a high-pressure water spray, in which condition it is used for fill or in the manufacture of cement. The flue dust, collected from the dustcatcher, the primary and secondary cleaners, is usually recovered and sintered and then returned to the furnace. . . .

"At the present time furnace tops are somewhat complicated affairs . . . (the older charging arrangement was) improved by the *double bell* and hopper. . . . Essentially, this improvement consisted in placing a second but smaller bell and hopper above the first, and providing a gas-tight space of large size between the two. The raw material, upon being hoisted to the top, is first dropped or dumped into the upper hopper, whence it may fall into the larger hopper below when the small bell is lowered. The small bell being raised against the upper hopper, the large bell is lowered, and the charge falls into the furnace without the escape of gas. . . .

"For the escape of the gases, from 2 to 4 large openings, called *offtakes*, are provided. They pierce the furnace top just about the level of the big hop-

[1] J. M. Camp and C. B. Francis. The Making, Shaping and Treating of Steel. U. S. Steel Co., 6th Ed., extracts from pp. 283-309 (1951).

per. From these openings, about 6 ft. in diam., abrasion-resistant steel or firebrick lined pipes lead into one large pipe called the *downcomer* or *downtake*. Bleeders located usually on top of the vertical uptakes . . . are really valves which are adjusted, either by weights or by mechanical means, to open at a certain selected pressure. They are designed to relieve excessive pressure (and so prevent possible injury to the top) occasioned by *slips* in the furnace . . .

"**Stoves.** Blast-furnace stoves, usually 3 per furnace, are brick-lined regenerators enclosed in a circular steel shell with a flat bottom and a dome-shaped top. Their function is to preheat the blast before its admission into the furnace through the tuyeres. The result of preheating the blast is to intensify and speed up the burning of the coke at the tuyedes with a consequent reduction in the coke required for the smelting operation. . . . Essentially, a stove consists of 2 parts: the first being the combustion chamber which is a passageway in which the burning blast-furnace gas passes upwardly, extending from a point near the bottom of the stove to the bottom of the dome; and the second being the brick checker-work which contains a multiplicity of small passageways through which the products of combustion from the blast-furnace gas pass downwardly to a point near the bottom of the stove. . . .

"Modern stoves for large furnaces are 26 to 28 ft. in diam. and about 120 ft. from the bottom to the top of the dome. Depending upon the type of checkers used, the stoves contained between 250,000 and 275,000 ft.^{2} of heating surface. . . .

"Blast for the furnaces passes through the stoves heated in the previous cycle and in a reverse direction. In a 2-pass stove the gas passes upward through the combustion chamber, downward through the checkers and out to the stack. In the following cycle, the blast passes in a reverse direction upward through the checkers, downward through the combustion chambers, and out into the hot-blast main. With 3 stoves to a furnace, one stove is *on blast* at a time while the other 2 stoves are *on gas* with the result that each stove is *on gas* twice as long as it is *on blast*."

Dust Emissions from Blast Furnaces

There are, in the main, 2 potential types of dust emission incident to the operation of blast furnaces, both of which have been greatly reduced in importance over the years. One is the residual dust in blast furnace gas which would pass to the atmosphere in the flue gases from the combustion of the gas. The other is the occasional escape of dust-laden gas from the bleeder openings of the furnace for reasons of safety during brief episodes called *slips*. The conditions which are associated with dust escape in each instance represent an important economic loss and have consequently received considerable attention over the years from the steel plant operators.

Blast Furnace Flue Gas Dust. The fine particles of the stock, principally the fines fraction in the iron ore, tend to be entrained in the high velocity gas streaming between the interstices of the stock bed inside the furnace and are carried out of the furnace in suspension in the blast furnace top gases. The top gas from a blast furnace contains a high proportion of the total heat input to the furnace and must be recovered to permit economic operation of the blast furnace itself. It is universal practice, therefore, to burn this gas productively in various items of auxiliary equipment. For each ton of iron produced, 150,000 ft.^{3} of gas is generated, having a heating value of around 100 Btu./ft., which is about 1/10 of the heating value of natural gas.

About 20% of the gas is required for the stoves which pre-heat the air blast for the furnace. The remainder may be burned as fuel under boilers for steam generation, it may be used for the under-firing of coke ovens, and for the heating of soaking pits. In years gone by it was also commonly used for the direct operation of reciprocating blowing engines which supplied blast air to the furnace.

In each of these applications the presence of dust seriously interferes with efficient utilization of the heat value in the gas. It has consequently been the practice in modern times to clean the gas and with the advance of steel plant technology over the years the operations have required that more and more of the gas be cleaned in a secondary stage also.

In the stoves, improvements in the utilization of the gas heat value has come about due to the use of refractories with smaller passageways for the hot gases; and with this development it was necessary, simultaneously, that the dust content of the gas be reduced to low values in order to avoid clogging.

The gas cleanliness requirements for the blowing engines were always rigid (less than 0.02 gr./ft.^{3}). The use of blast furnace gas in under-firing of coke ovens requires that a high standard of gas cleanliness for the same reasons as apply to the stoves.

Even for fuel burned under boilers for the generation of steam, there are compelling economic reasons for cleaning the gas. This stems from the fact that deposits of dust on the heat exchange surfaces tend to insulate them and retard heat flow resulting in the production of less steam for power due to the lower thermal efficiency of the boiler.

Blast furnace gas cleaning is usually effected in 2 stages. The primary gas washer consists of a simple type of water scrubber involving passage of the dusty gas stream through water sprays in various mechanical arrangements. This unit can be expected to remove some 90% or more of the entering dust, mostly the coarser fraction. The use of primary gas cleaning is almost universal practice in the operation of blast furnaces and in the most effective apparatus, the gas leaves the primary washer with a dust content of 0.1 to 0.3 gr./ft.^{3}

Blast furnace gas fine-cleaned in modern secondary gas cleaning apparatus, has a dust content of no more than 0.01 gr./ft.^{3} and as a result the dust emitted to the open atmosphere with the burned waste gases amounts to less than 10 lb./hr./furnace. For all practical purposes this is insignificant. Nearly all of the blast furnace gas in the U.S. is cleaned in primary gas washers and a major portion also is fine-cleaned in secondary washers or precipitators.

"Secondary gas cleaners have consisted of wet-type Cottrell precipitators, high-speed disintegrators, and Theissen disintegrators. Formerly, Theissen disintegrators were used almost exclusively, but on later installations have been replaced by high-speed disintegrators or by the wet-type Cottrell precipitators, with preference being given to the latter type."[2]

Riddle[3] comments on gas cleaning developments as follows:

"Primary dust catchers have been designed for greater size and improved dust removing ability . . . . The design of tower gas washers also has progressed and in some installations the

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[2] Ibid, p. 314.

[3] L. E. Riddle. Improvement in Blast Furnaces in the Past Quarter Century. *Blast Furnace & Steel Plant*, p. 87 (Jan. 1946).

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There is considerable economic incentive for fine cleaning of blast furnace gases regardless of the site of combustion. Primary gas cleaning repays its cost in most instances in a relatively short time. The economics of fine cleaning depend upon fuel requirements of auxiliary furnaces. If there is a use for all the gas then economic returns can be expected in this case also, although at a lesser rate than in the case of primary gas washing.

Blast Furnace Slips. Hanging of the charge in a blast furnace with its following slipping is one of the most troublesome of blast furnace problems. It causes decreased production, increased cost in that it increases the fuel consumption because it is always necessary to add fuel to overcome the ill effects of hanging and it increases the loss of iron ore carried out in the sudden burst of velocity of the outgoing gas. It also is the main cause of making off-grade iron so that economically it is probably the one thing above all others that has to be controlled. To protect the furnace structure pressure relief valves (bleeder valves) are provided which open automatically and permit the escape of gas to the atmosphere until conditions have corrected themselves. Considerable amounts of dust are blown out in the escaping gas stream.

The conditions which give rise to slips and consequent dust escape are extremely complex and have engaged the attention of blast furnace operators for decades. There has been a constant and continuing effort to minimize them because of the cost in lost production. Furnace operation is seriously affected for long periods preceding and following the actual slip itself. In other words, the seriousness of the slip from the standpoint of furnace operation is far greater than is indicated by the relatively short time period during which the bleeder valves are open for pressure relief.

An extended discussion of the nature and causes of slips is given by Willcox.[4] A more recent discussion of furnace conditions related to hanging and slips in British practice is given by Elliot *et al.*[5]

Reduction of Dust from Slips

In large segments of the industry important advances in blast furnace

technology have contributed considerably to a reduction in frequency of those slips which caused bleeder valves to open and permit the escape of dust to the atmosphere. In some blast furnace operations dust escape due to this cause has decreased to completely unimportant proportions. It is not possible to state which of the following improvements has contributed most to control of such dust emissions but each has had a favorable influence.

Coal Washing. The washing of coal before charging to the coke ovens to reduce ash and sulfur content has become increasingly common with the discovery of its advantage in resulting coke quality. The reduction in ash content results in a lesser contribution of slag constituents from this source which has beneficial effects on blast furnace operation. Smooth operation of the blast furnace means fewer *hanging* episodes and therefore less frequent operation of the bleeder openings, the safety valve of a blast furnace.

Sintering. One of the most important factors contributing to furnace irregularity and consequent dust escape through bleeder openings is in the size characteristics of the furnace ore charge. A high proportion of fines in the ore enhances the chances of *hanging* and subsequent slipping. In recent years changes in the character of U.S. ore supplies created potential production problems due to a greatly increased amount of fines. This has led to widespread practice of sintering the fines which are separated from the raw ore by screening. The consequence is that blast furnaces are increasingly being supplied with charges containing less fines than ever before with resulting beneficial effects on furnace operation and slipping frequency and this also means less escape of dust to the atmosphere.

Informative discussions of these developments in ore sintering have ap-

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(2) F. H. Willcox Blast Furnace Breakouts, Explosions and Slips and Methods of Prevention. U. S. Bureau of Mines Bulletin No. 130, pp. 184-199 (1917).

(3) G. D. Elliot, *et al.* Iron Making at the Appleby-Frodingham Works of the United Steel Companies, Limited. Special Report No. 30, the Iron and Steel Institute, pp. 182-208 (1944).

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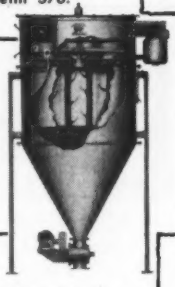

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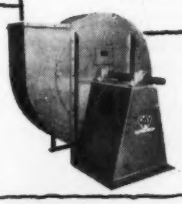

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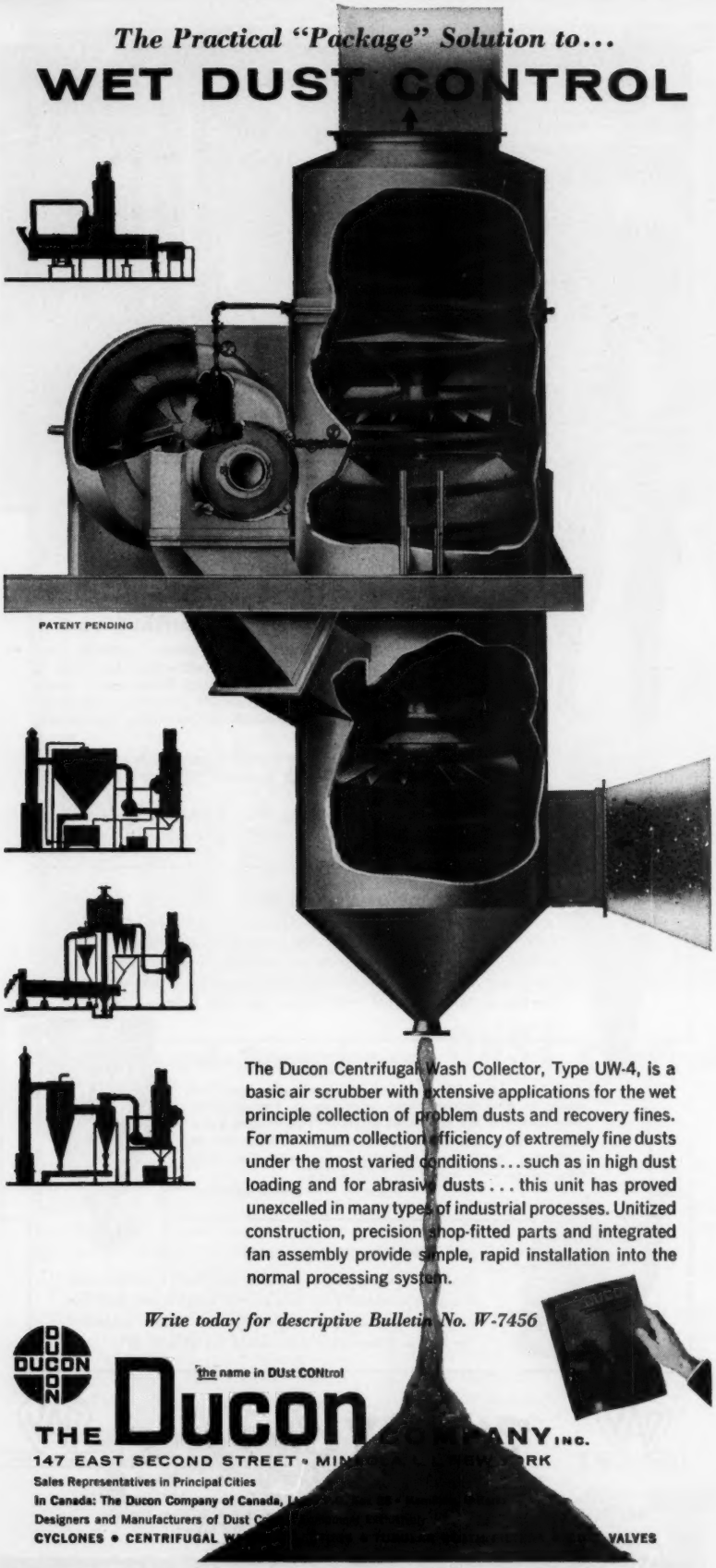

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peared in the technical literature in recent years [6,7,8,9,10].

Clean Gas Bleeding. Another practice for reducing air pollution which is becoming more and more common involves arrangements for venting gas pressures due to slips by opening a bleeder communicating directly with the clean side of the gas washer except for slips of greater intensity requiring relief directly through the bleeders on the top of the furnace. This device has been particularly effective on high top pressure blast furnaces which have been placed in operation in considerable numbers in recent years.

A bleeder valve is provided on the clean gas end of the gas washer and the opening mechanism arranged to be actuated by the pressure sensing element on the top of the furnace. This results in the opening of the clean gas bleeder before the pressure wave has completed passage through the flues leading to the gas washer. Pressure response instruments on the furnace uptake are designed so that the lesser pressures due to slips are vented through the clean gas bleeder. The higher pressures which occur more rarely must still be vented directly from the furnace top for reasons of safety. The control system as applied to high top pressure furnaces was described by Murray[11] as follows:

"This bleeder valve is a motor-operated positive seating valve. The mercoid switch controlling the operation of the clean gas bleeder valve is set to operate at a pressure lower than that for the mercoid switches controlling the standard dirty gas bleeder valves. For example, under 11 psi. top pressure furnace operation, the clean gas bleeder

---

(6) H. F. Dobacha. Effect of Sixed and Sintered Mezabi Iron Ores on Blast Furnace Performance. *Proc. Blast Furnace, Coke Oven & Raw Materials Committee of Iron & Steel Div.*, (Am. Inst. Min. & Met. Eng.), 7, 49 (1948).

(7) A. H. Fosdick. Screening & Charging Practice Increases Furnace Yield. *Steel*, p. 86 (June 18, 1951).

(8) M. W. Lightner. Burdening the Blast Furnace. *Steel* (Feb. 7, 1955).

(9) J. A. Bond, and T. Sanderson. Full-Scale Blast Furnace Trials. *J. Iron & Steel Inst.*, p. 24 (May 1951).

(10) Owen R. Rice. Some Aspects of the Blast Furnace Situation in the United States. Part II, *Blast Furnace and Steel Plant*, p. 658 (June 1952).

(11) John C. Murray. Progress at Republic Steel Corporation with the High Pressure Blowing of Blast Furnaces. *Blast Furnace & Steel Plant*, p. 49 (Jan. 1953).

DUST AND FUME CONTROL

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CONSULTING ENGINEERS

DUST AND FUME CONTROL
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valve would be set to open at approximately 14 psi, and the dirty gas bleeder valves set at 16 psi. and 17 psi. respectively. Thus, when the furnace slips, pressure relieving is accomplished by the clean gas bleeder valve, and the dirty gas bleeder valves will be opened only in those rare cases of very high slip pressure. It has been found that this arrangement prolongs the life of bleeder valves indefinitely and eliminates the problems resulting from bleeding dirty gas into the atmosphere.

On high top pressure furnaces, the use of power operated bleeder valves and the greater latitude allowable on gas pressures greatly facilitates the operation of the clean gas bleeding system. The same system can, however, be applied to most other furnaces not on pressure blowing[12] (exceptions appear in the case of some old furnaces not designed to withstand excess top pressures) and this has been done extensively in recent years.

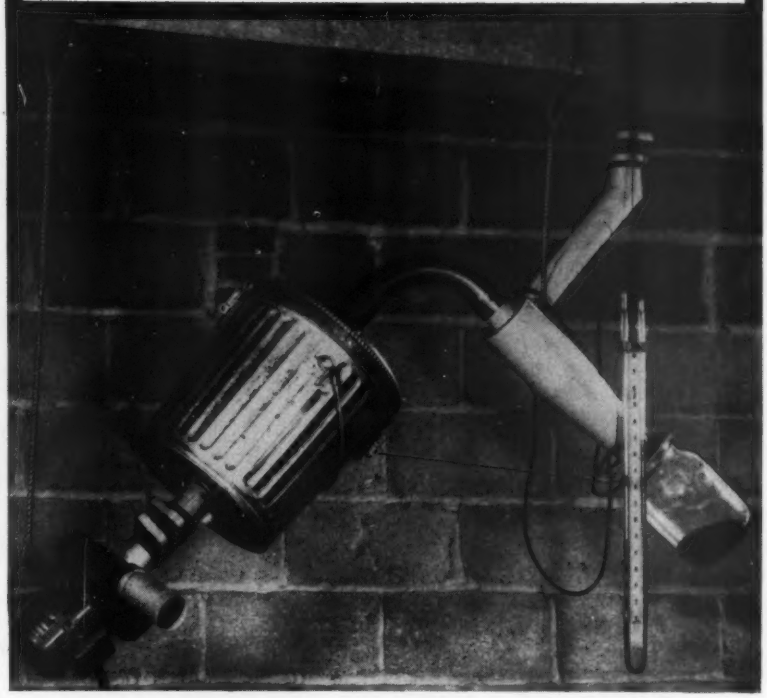
Weighting Bleeder Valves. The loading on the bleeder valve determines the magnitude of the pressure required to open it. Since the function of the bleeder is to protect the furnace from rupture due to excess pressures, the maximum degree of loading on the bleeder valve is properly determined by reference to the design strength of the furnace shell and its appurtenances. The newer furnaces are designed to withstand considerably greater pressures than older ones.

Some blast furnace operators have found that their bleeder valve loading could be materially increased without danger to the furnace and hence by adding weight to the valves have reduced the frequency of bleeder valve opening; more of the slip pressures are contained completely within the system.

---

[12] Frank Janecek. Five Years of Blast Furnace Operation under Elevated Top Pressure. *Iron & Steel Eng.* p. 55 (Jan. 1950).

This Simple Test can
CLEAR-THE-AIR
of perplexing dust problems



● In your official capacity as an air pollution control official or plant dust control engineer, you'll welcome this Dustex test method that affords the opportunity of sampling greater air or gas volume, thus increasing test accuracy. Also, collection efficiencies and amount of recovery attainable with Dustex equipment can be determined *before* selection of collectors. This test method takes away the *maybe?*...gives you positive, quantitative results.

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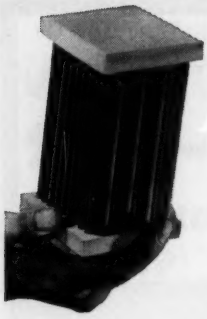


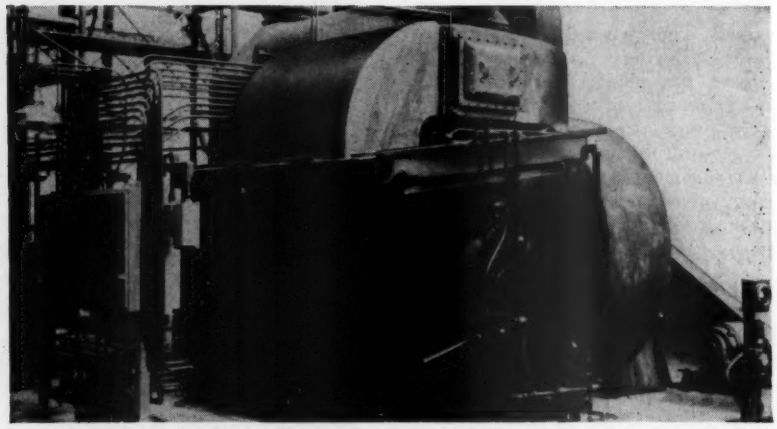
An important message to the man who thinks his air pollution problem is too difficult—or too expensive—to correct

Too often an air pollution problem exists today for one reason only: The company concerned does not yet know there is now at hand an efficient, effective method of correcting it—often at an actual saving through waste heat recovery.

The method is catalytic oxidation, and the firm that makes this development possible is Oxy-Catalyst, Inc.

Catalytic oxidation works by "burning" harmful and irritating combustible contaminants in an exhaust stream at temperatures far below their normal ignition points. It provides close to 100% cleanup of foul-smelling fumes and odors. It reduces fire hazards and maintenance problems by eliminating troublesome condensates in oven and furnace exhausts.

Thus Oxy-Catalyst installations can not only control air pollution. They can also be used to release the latent heat energy in waste and process gases. And they can sometimes do both at once.



Oxycat Installation on Standard Oil Company of California's phthalic anhydride unit at Richmond, Calif.

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The key to successful catalytic oxidation is, of course, the catalyst itself. Features which make the Oxycat unique are:

- *The combination of platinum and alumina, chosen from hundreds of elements and compounds as the most active and long lasting catalytic agent*
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- *The patented method of applying the catalyst to the carrier*
- *The patented mechanical design of the Oxycat itself*

The result of this combination of features is a catalytic unit with exceptionally long life at high efficiency. Oxycats are strongly resistant to thermal shock—to contaminating agents and clogging. There's no problem of frequent cleaning or reprocessing. Oxy-Catalyst installations are still functioning at high initial efficiency after over 20,000 hours without maintenance or servicing.

Already in Wide Use

Oxy-Catalyst installations are now working effectively in a wide range of industries—oxidizing combustibles from such processes as asphalt oxidation; phthalic anhydride, polyethylene and ethylene oxide manufacturing; catalytic cracking; and many others.

Oxy-Catalyst installations are carefully engineered to your individual requirements, and our engineers, working with yours, can install Oxycats effectively in any existing plant. So, if air pollution is a problem in your operation—if irritating fumes and odors are costing you neighborhood good will—you should know that Oxy-Catalyst offers a practical, realistic answer to your problem.

Fill in the coupon, or write on your business letterhead, for complete information now.

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Behind Koppers successful solutions to every type of industrial air pollution problem lies three-quarters of a century of research and development in this country and abroad. From all this "know-how" come the basic types of gas cleaning units, produced by Koppers, that can solve any gas cleaning problem you may have.

KOPPERS 75 Years' Experience can Solve Your Industrial Gas Cleaning Problem!

ONE REASON WHY KOPPERS can make this promise is that Koppers builds the basic types of gas cleaning units. But obviously, that's not enough!

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How Koppers got that knowledge and experience is a story in itself. By building gas handling equipment for over seventy-five years. By handling coke gases in Koppers own plants for over forty-five years. By successfully solving gas cleaning problems in every industry where they are a headache . . . in plants of all sizes, with a wide variety of individual problems. So . . . when a Koppers engineer studies your specific problem, you know he has this wealth of experience to draw upon. It helps make him the best gas cleaning engineer in the business.

To drive your costs down even further in the solution of gas cleaning problems, Koppers carries on a never-ending research program . . . creating new gas cleaning techniques . . . finding out more and more about the properties and composition of materials that pollute the air. That's the job of Koppers' multi-million dollar research center at Verona, Pa.

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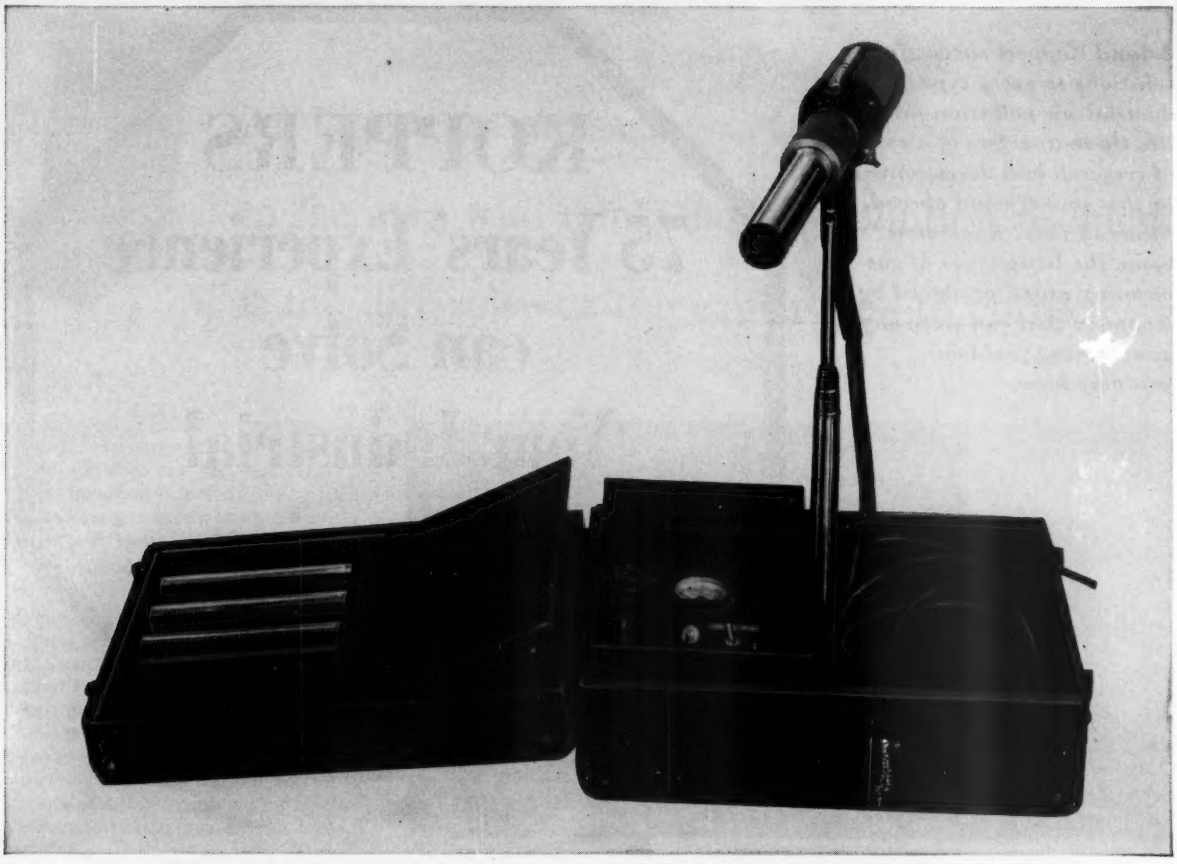
Koppers Aeroturn Dust Collectors. Automatic pressure control and reverse-air-jet action provide high, continuous filtering. Clean air, reclaimed materials. Felt-type filters are more efficient; last longer.



The M-S-A Electrostatic Sampler, complete with portable case, operates by plugging into any 110-115 volt outlet.

Determine harmful or nuisance contaminants in industrial atmospheres accurately . . . efficiently with the M-S-A® Electrostatic Sampler

M-S-A Electrostatic Sampler in actual field service.

This high efficiency instrument collects dusts, metal fumes, and smoke from industrial atmospheres. You can use the M-S-A Electrostatic Sampler in the ceramic, electrical, steel and chemical process industries and in industries engaged in the production of radioactive materials to determine harmful particulate contamination for industrial hygiene and air pollution studies.

Self-contained portable sampling head has a blower which provides a constant flow of 3 cu. ft. per minute when operating on a 60-cycle AC at 105 to 120 volts. The power pack is adequate for intermittent, short duration sampling or for long, continuous operation.

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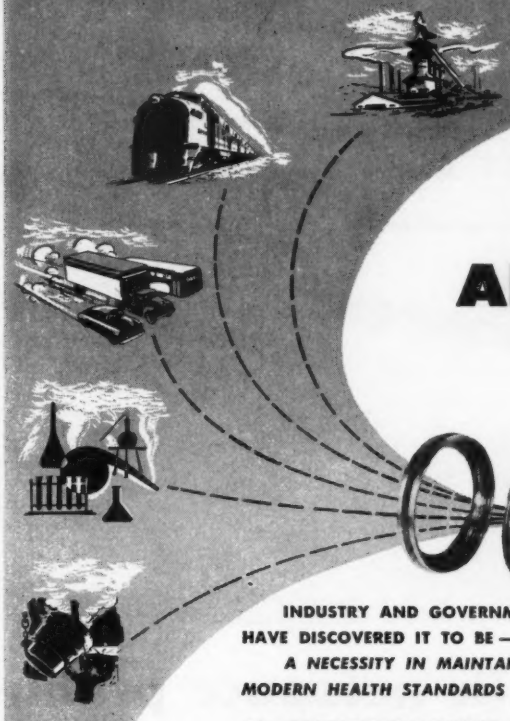

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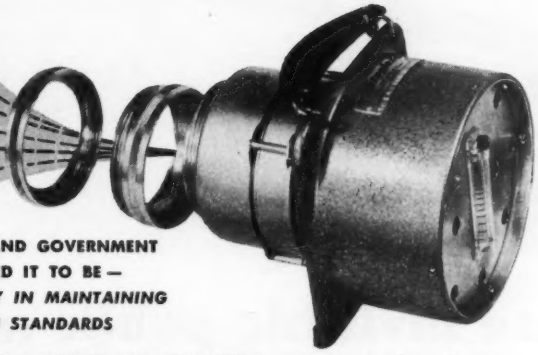

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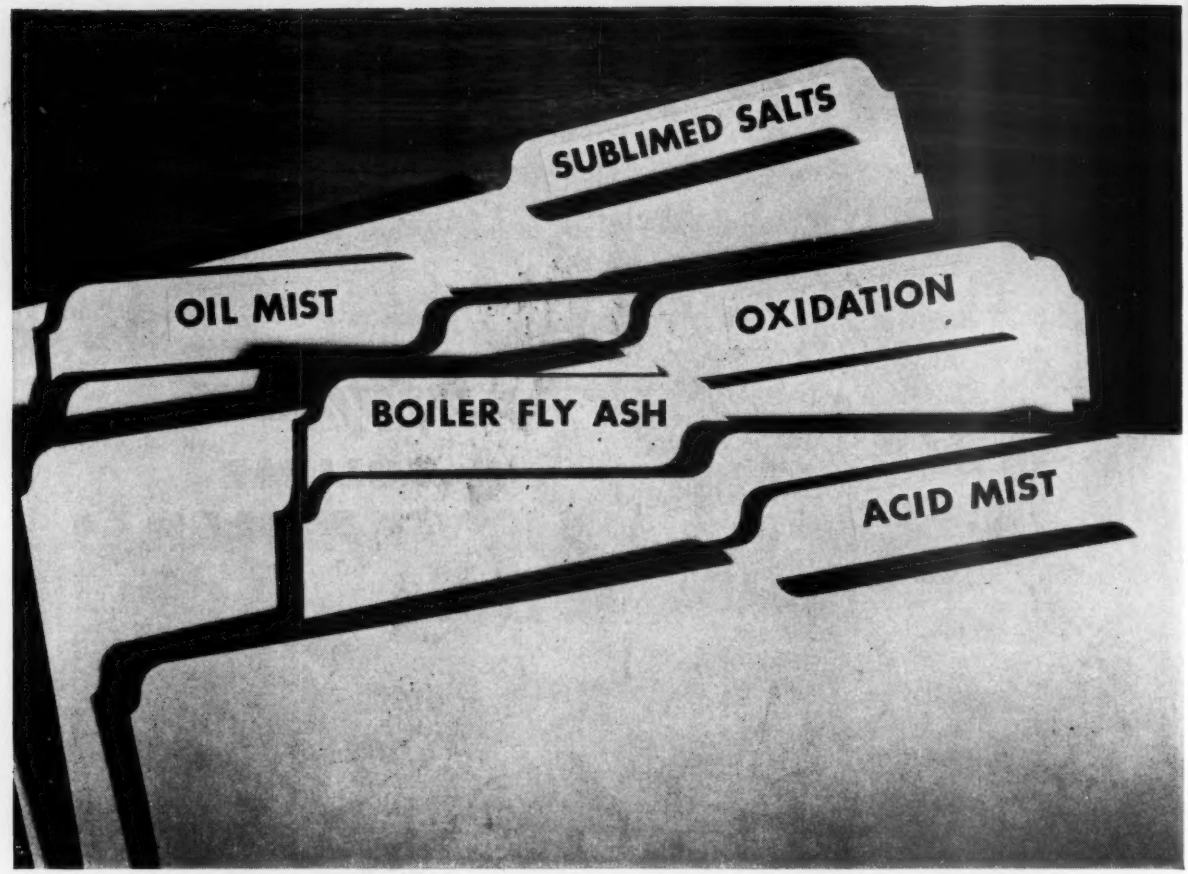

These invisible public nuisance problems can't be filed away!

THE absence of smoke clouds above an industrial stack is *no guarantee* that a major air pollution problem is not in the making. The "offspring" of plating tanks, salt bath furnaces, metalworking machines and boilers—mists, salts, metal dust, fly ash—seldom "advertise" their destructive powers. And they produce the very *worst* kind of pollution problem . . . the kind you don't see but *hear about,* from unhappy employees, irate auto and home owners.

The answer to this "creeping" air pollution is *complete* dust control—the unseen as well as the seen—with AAF equipment. Dynamic precipitators, hydrostatic precipitators, dry centrifugals, fabric arresters—all are in the AAF line, and all have their place in the fight against air pollution.

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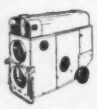
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How the Steel Industry Is Fighting Air Pollution

When the public hears about dust and fume control it is often in terms of what has *not* been done. It is important that they should also know what *has* been done, because the record of the steel industry is one of the most progressive.

The purpose of this discussion is to give the executives the facts to prove this point.

Q. *First of all, how can you measure the progress of dust and fume control in the iron and steel industry?*

A. As you know, there are many ways to combat air pollution. Equipment and methods vary in effectiveness, but the industry agrees that electrical precipitators have the highest collection efficiencies. By keeping track of the demand for this high efficiency equipment over the years, we can get a good indication of the importance the industry places on dust and fume control and the progress they are making.

Q. *Do these figures show an increasing interest in this high efficiency equipment?*

A. Suppose we let the figures speak for themselves. Since 1945 precipitator capacity in the steel industry had a greater increase than in any previous ten year period. Precipitators handling about 6½ million cfm were installed during this period.

Q. *But can't you attribute this growth to the increase in steel-making capacity?*

A. Some of this growth is due to expanded production facilities, but that's just a part of it. For instance, iron and steel production has increased about 30% since 1945 — but precipitator capacity has increased about 130% during this same period.

Q. *In the old days, I guess precipitators were used primarily in blast furnaces, weren't they?*

A. That's right. The first one went into operation in 1930. Since then, 169 Research Cottrells have been ordered by the industry.

Q. *What about new applications?*

A. We have a number of new uses that have proven themselves on the job. Open hearths, for instance. In one installation, our precipitators reduced stack discharge to a little over 2 pounds per hour. That's quite a reduction when you consider that the discharge without a precipitator ranged from 75 to 245 pounds per hour.

Q. *I understand your Cottrells are used on some sintering machines now. Is this true?*

A. Yes, we have three in operation and more under construction.

Q. *How about scarfing machines?*

A. This is a recent application which has worked out very satisfactorily. Two precipitators are now in operation on this application.

Q. *Has anything been done on such problems as iron cupolas, electric furnaces, and ferromanganese blast furnaces?*

A. Yes. Installations have been made on all these problems.

Q. *How do you go about developing these new applications?*

A. We work very closely with our customers on these new projects. Our laboratory is a big help, and our 40 years of pilot plant experience plus over 2,000 precipitators give us the kind of experience that leads to the successful engineering of projects like these.

If you would like to have more information about these applications, or if you want to investigate the possibility of using precipitators on other equipment, our nearest representative will be glad to call on you.

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